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Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa

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Foreword

Securing an adequate food supply and safe drinking water for people around the world is undoubtedly one of the greatest challenges of the 21st century. As much as 50% of the world's population relies on water supplied from transnational water systems. Additionally, water availability may be compromised by large-scale climate and land use changes that have significant impacts on global and regional water cycles. Together, these issues present a series of new challenges that necessitate developing sustainable strategies for water management and livelihood security.

The German Government and its Federal Ministry of Education and Research (BMBF) have played an active role in addressing these global challenges. To address these global issues, BMBF launched the Global Change and Hydrological Cycle (GLOWA) pilot program in 2000 as a part of the BMBF framework program on sustainability research. The objectives of GLOWA are to develop, test, and apply new integrative, interdisciplinary methods and models in individual projects. The methodologies and simulation tools developed under the program will contribute to long-term sustainable water management at the local and regional (river basins of approximately 100,000 km²) scales, taking into account global environmental changes and socio-economic conditions. Hence, Germany reaffirms its commitment to the United Nation's International Decade for Action "Water for Life" and to the Millennium Development Goals of halving the proportion of people without access to safe drinking water by 2015 and of eradicating extreme poverty and hunger. GLOWA is a prime example of programs intended to achieve these goals.

Two of the five GLOWA projects, GLOWA IMPETUS and GLOWA VOLTA, focused on river catchments in Africa, a continent which is generally considered highly vulnerable to adverse impacts from Global Change. Both projects successfully demonstrated the benefit of targeted research on application-oriented solutions to imminent water-related and food-related problems resulting from Global Change.

In this book, GLOWA IMPETUS provides a thorough overview of the wealth of its research results, how they were implemented into models and how meaningful projections of future developments can be established in sectors such as climate, water, agronomy, socio-economics, anthropology, and health. It has long been recognized that sustainable development must be based on scientific knowledge. The present book provides a good example of how GLOWA IMPETUS transferred interdisciplinary and integrated research into application-oriented, decision support tools. A coherent presentation of research results in this comprehensive publication will help to make its approaches, results, and "lessons-learned" known to a range of researchers and to the public.

Rainer Müssner
Federal Ministry of Education and Research / Germany

Acknowledgements

This publication is based on nine years of intense research carried out mostly in the Republic of Benin and the Kingdom of Morocco, and was funded by the German Federal Ministry of Education and Research (BMBF; grant No 01LW06001A/B) and co-funded by the Universities of Cologne and Bonn. The Ministry of Innovation, Science, Research, and Technology of the German State of North Rhine-Westphalia (MIWFT) has also demonstrated its strong interest in West Africa's sustainable developement in various sectors among which are especially education and science. This can be seen from the fact that MIWFT has strongly supported the African GLOWA projects over the years (MIWFT grant No. 313-21200200 for IMPETUS) and by the fact that on November 5, 2007 Ghana became a partner country of North Rhine-Westphalia.

It has to be underlined at this point that this work would not have been possible without the help, cooperation, and support of many individuals, colleagues, government/non-government organizations, and institutions too numerous to list here. For further details, see: www.impetus.uni-koeln.de/projekt/kooperationspartner.html.

We would like to extend a special thanks to the German Embassies in Benin and Morocco for their advice and support, to Thierry Lebel and Christian Depraetere from the CATCH/IRD project for their generous help in setting up the project in Benin, and to all members of the respective Steering Committees in Benin and Morocco for their valuable contributions during numerous meetings. Finally, we would like to thank all the reviewers of the IMPETUS project. Their constructive comments and guidelines significantly contributed to the success of IMPETUS.

Cologne and Bonn, March 2010 The Editors

Preface

Africa is an economically poor continent, contributing less than 2% to the world gross national product while holding more than 15% of the world population, with the population growing rapidly. Despite efforts by African countries, the amount of freshwater and food available per capita has steadily decreased over the past several decades. The reasons for this are numerous and complex. Africa has suffered from continual neglect over the centuries, both from the socio-economic and scientific points of view. Thus, it would be quite unrealistic to believe that solutions to water-related problems could be simple and achieved quickly. We are convinced that sustainable solutions to Africa's most pressing problems have to be science-based and implemented in a holistic and integrated approach that involves relevant disciplines from the natural, socio-economic, and health sciences. Another important element of sustainability is the efficient transfer from *science to application*. The IMPETUS research project has pursued this pathway successfully for almost 10 years and was structured into three research phases, as described below.

The first project phase was dedicated to data acquisition and to the comprehensive assessment of the *status quo* (i.e., the identification of existing water-related problems together with their underlying physical processes and interdependencies). In the second phase, qualitative and quantitative models were adapted or newly developed. Projections of future developments were derived from scenario calculations and from expert knowledge. In the third phase, tailored tools for local decision makers were developed to enable sustainable natural-resource management. A supplementary phase concentrated on the implementation and operationalization of research results. The transfer of knowledge and the intense capacity development undertaken were intended to facilitate African citizens to take responsibility for sustainable development.

The present publication entitled, "Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa", is based on the long-term applied research experience of IMPETUS in two African watersheds: the Ouémé catchment in Benin and the Drâa catchment in Morocco. This publication is targeted for the following audiences: (i) scientists interested in state-of-the-art interdisciplinary research on the hydrological cycle who would like to obtain insight into neighboring disciplines; (ii) application-oriented scientists interested in knowledge transfer to application from an exemplary integrated research project, including how such a project could be designed conceptually, and (iii) decision makers with some scientific background who wish to learn how sound research results can be incorporated into the decision making process in the context of natural resource management and Global Change.

We hope this publication is welcomed and accepted in both scientific and non-scientific communities, and that it spurs interest in application of water management principles to aid Africa.

Cologne and Bonn, March 2010 The Editors

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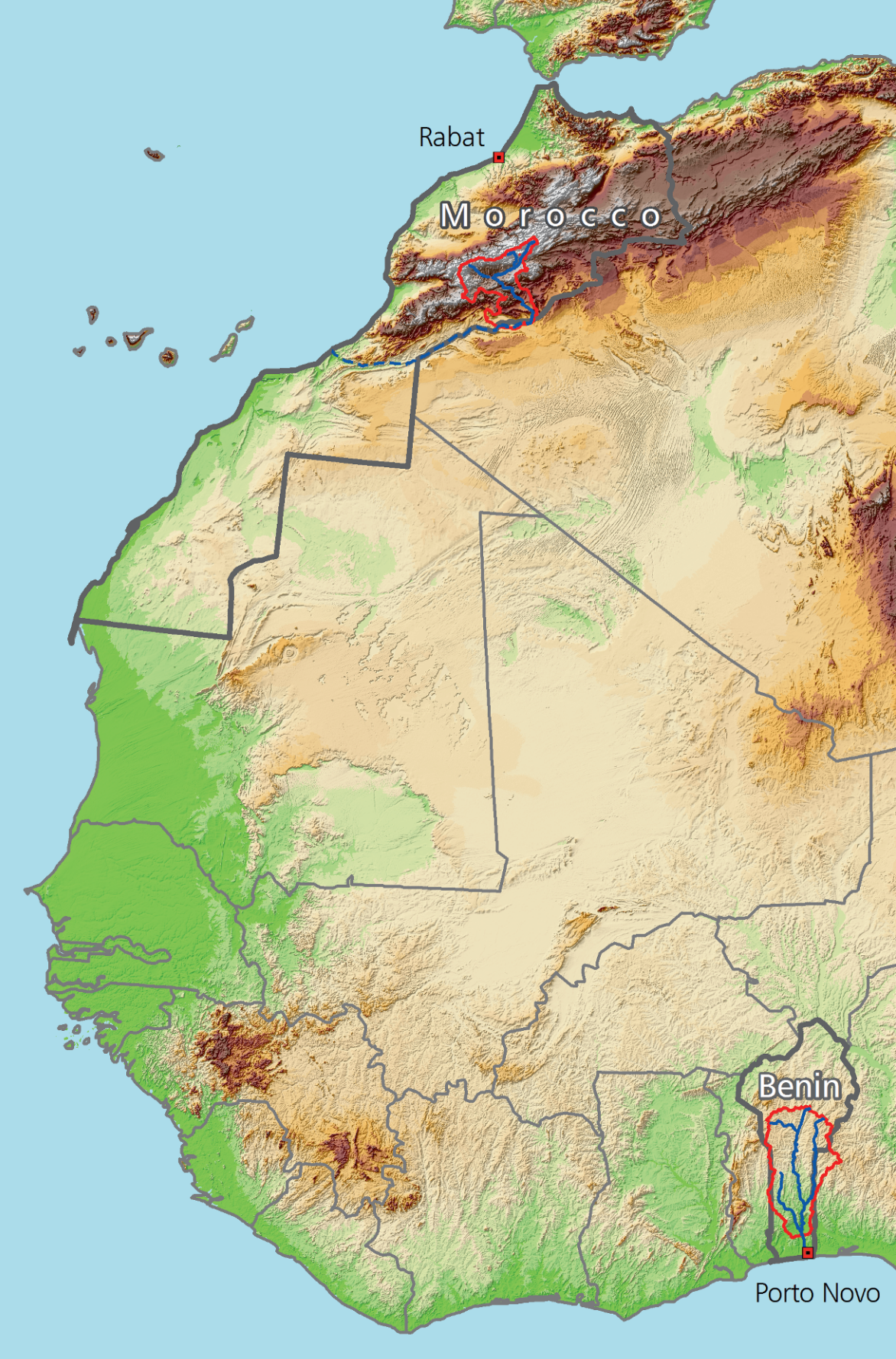
Part I

Fundamentals and process understanding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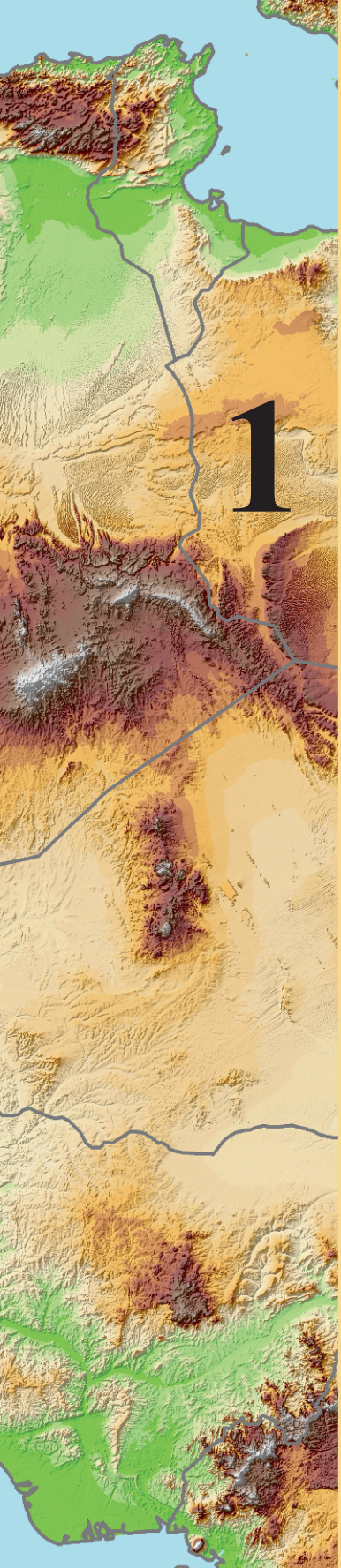

1 Introduction

I-1 Introduction

P. Speth and A. H. Fink

Human activity affects the Earth's climate mainly via two processes: the emission of greenhouse gases and aerosols and the alteration of land cover. Climate research conducted in the past several years indicates that most of the observed increase in global average temperatures over the past few decades is *very likely*[1] due to the observed increase in greenhouse gas concentrations from human activities. It is *likely* that without the cooling effects of atmospheric aerosols, greenhouse gases alone would have caused a greater global temperature rise than has actually been observed. Research also indicates that human influences on the climate are expected to increase in the future, mainly because greenhouse gas emissions will continue to rise. Consequently, global average surface warming is projected for the 21st century. These projections depend largely on the scenarios used to represent greenhouse gas emissions. In general, however, the projected warming is greatest over the land and most high northern latitudes, with relatively less change over the Southern Ocean and parts of the North Atlantic Ocean. Warming is typically projected to be greater in arid regions than in humid regions. Projected precipitation increases are *very likely* at high latitudes, while decreases are *likely* over most subtropical land regions. This projected change in precipitation is a continuation of recent trends.

The above-mentioned projections for Climate Change are based on coarse-grid, global-scale climate models with a spatial resolution that is typically greater than 200 km. These models only consider greenhouse gas forcing and usually do not consider land use changes (or at least only do so in a cursory manner). Climate Change is part of Global Change, which consists of three components: demographic change, global environmental change, and globalization impacts. In this context, environmental change refers to climate variability and Climate Change, land use and land cover change, changes in water availability and loss of biodiversity. Processes behind Global Change are interdependent and interrelated, and they interact in complex ways. Thus, interdisciplinary[2] studies are necessary to find solutions to Global Change-related problems.

Observational evidence shows that many natural systems are affected by Global Change, among which the hydrological system is predominantly influenced. Because of the aforementioned projected large-scale patterns of precipitation and warming, it can be postulated that Global Change will impact the hydrological

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[1] In The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) the likelihood of an outcome or result where this can be estimated probabilistically is defined as follows:
very likely: > 90% probability;
likely: > 66% probability.

[2] An *interdisciplinary field* is a field of study that crosses traditional boundaries between academic disciplines or schools of thought as new needs and professions have emerged.

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cycle and the availability of fresh water. A shortage of fresh water is expected to be the dominant water problem of the 21st century. Water shortages coupled with reduced water quality may jeopardize efforts to secure sustainable development. This may lead to social and political instability in some cases. Fresh water has already become critically scarce in many regions of the world. The global mean water withdrawal per capita has decreased significantly in recent decades. Some countries have renewable fresh water resources under 1000 m^3 per capita per year, which is a value that is commonly accepted as a benchmark for fresh water scarcity. It is estimated that one quarter of the world's population will suffer from severe fresh water scarcity during the first quarter of the 21st century. Therefore, this book focuses on the hydrological cycle in West and Northwest Africa for the following reasons: i) these regions have experienced the most pronounced inter-decadal climate variability of anywhere in the world during the 20th century; (ii) climatic alterations in Africa may impact the European climate via complex atmosphere-ocean interactions in the area of the tropical and extratropical North Atlantic Ocean; and (iii) the study regions contain sub-regions to the north and south of the Sahara that are linked by atmospheric teleconnection processes with regard to precipitation anomalies[3].

Investigations were carried out through an initiative named IMPETUS ('An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa', in German: '**I**ntegratives **M**anagement-**P**rojekt für einen **E**ffizienten und **T**ragfähigen **U**mgang mit **S**üßwasser in West Afrika'), which was a joint venture of the Universities of Cologne and Bonn, Germany. The work done under IMPETUS was part of a German research program on the global water cycle (GLOWA). GLOWA was launched by the German Federal Ministry of Education and Research (BMBF) and its aim was to develop strategies for sustainable future water management at regional levels while taking into account global environmental changes and socio-economic framework conditions.

Past and present situation

Tropical West Africa has suffered from declining rainfall since the late 1960s. Severe drought periods occurred in the early 1970s and in the first half of the 1980s. The average rainfall deficit from 1971-1990 was about 180 mm/year compared to the 1951-1970 interval. All climatic zones in West Africa have been affected, ranging from the semi-arid Sahel and the sub-humid Sudanese zone south to the humid Guinea coast. In addition, areas to the north of the Sahara desert have experienced a number of dry years since the 1970s. By the end of the 20th century, river discharges in West Africa had decreased by about 40-60% compared to 1951-1970, resulting in water shortages for domestic and agricultural

[3] For the existence of such a link by atmospheric moisture transports out of the area of the Inter-Tropical Convergence Zone (ITCZ) over the Western Sahel zone northward across the Sahara towards the Atlas Mountains, see fig. I-5.2.7.

purposes. These precipitation changes have led to extensive migration. During the rain-rich 1950s and 1960s, water power stations were built along the Guinea coastal zone to supply a substantial amount of energy to West African countries. Low discharges from major tributaries are the main reason for the recent frequent shortages in energy production. The decadal drought at the end of the 20th century clearly demonstrated that climate deterioration can cause a profound decline in the economic and social development of West African countries. A slow recovery of rainfall to near normal conditions has been observed in parts of the Sahel since about two decades. However an unabated drought period has been experienced in the western Sahel. Population growth and projected rainfall declines linked to anthropogenic Climate Change may provide no relief to pressing water problems in the long term – despite the present climate amelioration.

Apart from the per capita decrease in the availability of fresh water, the current situation to the north and south of the Sahara is also characterized by growing populations (e.g., population growth rates greater than 3% per year in Benin), increasing degradation of natural vegetation due to overgrazing (Morocco[4]), increasing demand for firewood, and shifting cultivation patterns (e.g., Benin). Soils have rapidly eroded in Morocco (and to a lesser degree in Benin), and salt content has risen due to intensive irrigation practices. In combination, these issues are likely to accelerate degradation and desertification processes in the coming decades. This situation is aggravated by increasing water demands, mainly associated with high population growth, which dramatically reduces the per capita water availability.

West Africa is one of the most vulnerable regions to desertification in the world. Desertification is characterized by land degradation that decreases agricultural productivity, reduces biodiversity, and degrades the environment, all while diminishing ecosystem resilience. Desertification is creating economic, environmental, and social hardship for millions of poor farmers practicing subsistence agriculture in fragile environments. The desertification of West Africa fuels the migration of people from the north to the south, thereby exacerbating problems in sub-Saharan Africa. This chain of events could potentially lead to social and political instability. Arable lands in this region are estimated to decline by 61% to 0.63 hectare per capita between 1990 and 2025.

Regionalization of climate projections

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) projected an overall warming trend in Africa and a substantial drying of subtropical North Africa based on global circulation models that use different emission scenario runs to the end of the 21st century. The rainfall trend

[4] This book deals with the water balance in two catchments in Benin and Morocco. Sometimes in the text, it is referred to these countries rather than to the catchment names (see below).

over tropical West Africa for this century is uncertain. For example, a comparison of individual global climate models used in the AR4 reveals considerable differences in their projections of rainfall trends in West Africa. A regional downscaling[5] of global climate models that takes into account land use changes (e.g., deforestation, desertification, vegetation loss, and soil degradation) indicates that a general decrease in rainfall together with prominent surface warming can be expected for sub-Saharan Africa[6]. Although rainfall will decrease north of the High Atlas Mountains and the Antiatlas Mountains, a somewhat wetter climate south of these massifs is suggested for the coming decades[7]. The projected wetter climate is a consequence of tropical-extratropical interactions (TEIs)[8] across the Sahara desert and is in contrast to the trends predicted by the IPCC global models.

The projected rainfall decline in sub-Saharan Africa indicates that the hydroclimate in tropical and subtropical West Africa will be impacted. This change suggests a weakening of the hydrological cycle. The implication of this precipitation reduction is that the decrease in fresh water availability will occur simultaneously to an increasing water demand. Agricultural production and food access are anticipated to be severely compromised. Decreases in agriculturally suitable areas, growing season lengths, and potential crop yields are expected, particularly along margins of semi-arid and arid areas. This condition would further adversely affect food security and exacerbate malnutrition.

Choice of catchments

During the IMPETUS project, thorough investigations of all aspects of the hydrological cycle were carried out along a transect between the High Atlas Mountains and the Gulf of Guinea for two river catchments in West and Northwest Africa: the river Ouémé in Benin and the wadi Drâa in the southeast of Morocco (see fig. I-1.1). These river catchments were chosen according to the following criteria: feasibility (< 100,000 km^2), availability of pre-existing data sets, political stability, relevance, and representativeness. Specifically, the Drâa catchment is typical of a gradient from humid/sub-humid subtropical mountains to arid foothills. The Ouémé basin in Benin is typical of a sub-humid climate ("Guineo-Soudanien") of the outer tropics with distinct dry and wet seasons embedded in a transect that extends from the Sahelian to the Guinean coastal climate.

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[5] For the different downscaling methods see subsections II-3.2.5 - II-3.2.7.

[6] See fig. II-3.2.6.

[7] See fig. II-3.2.12.

[8] See sect. I-5.2.

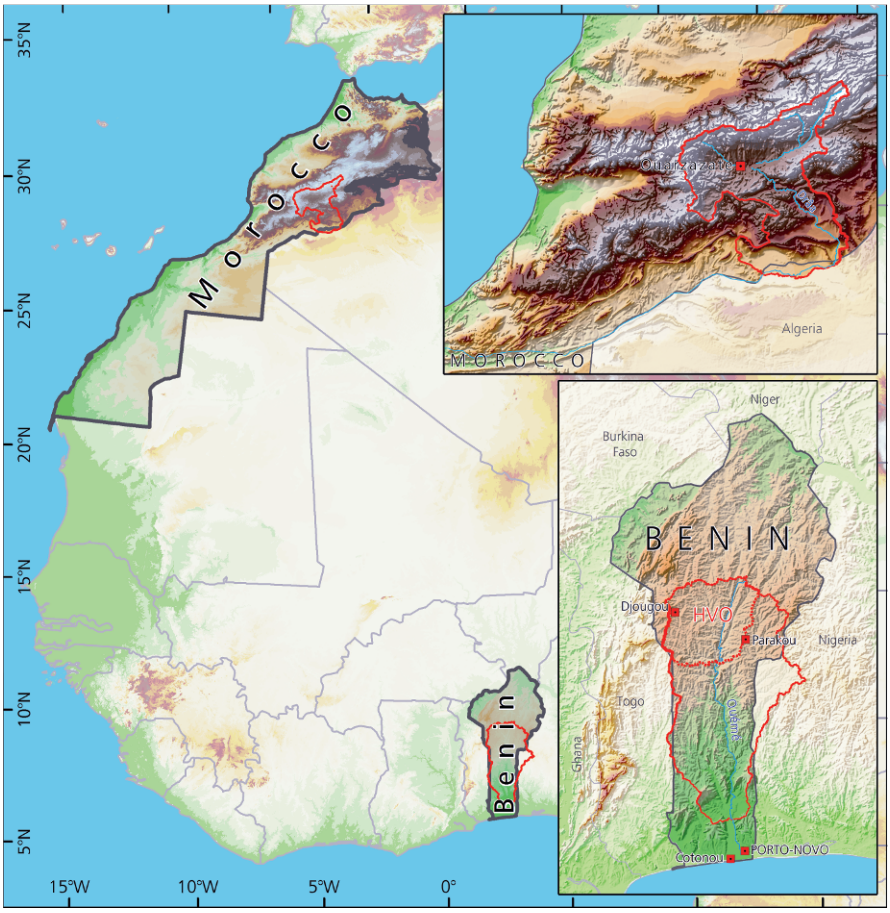

Fig. I-1.1: The two river catchments considered in this study, the Drâa catchment in Morocco and the Ouémé catchment in Benin, are outlined in red. A subcatchment of approximately 100x100 km west of Parakou has been chosen as an area of focused investigations (Upper Ouémé Valley / in French: *Haute Vallée de l'Ouémé* - HVO).

Options for a sustainable development

The overarching goal of IMPETUS was aimed at developing an interdisciplinary, integrative approach to mitigate regional-specific risks of Global Change as they relate to the hydrological cycle of the Drâa and Ouémé catchments. Ultimately, decision makers in Benin and Morocco were given tools that helped them to analyze decision-making problems and the underlying phenomena. This then allowed these parties to assess the impact of their decisions and to implement sustainable management options for the water resources that are so vital to life. The results of these different options can be compared and evaluated for different

scenarios, mainly with the aid of *Spatial Decision Support Systems (SDSSs)* but also with *Information Systems (ISs)* and *Monitoring Tools (MTs)*.

Outline of the book

This book adopts the interdisciplinary and holistic approach necessary to solve present and potential future problems regarding fresh water supplies. Interdisciplinary, application-oriented tasks were accomplished with the help of a unique mix of scientists from the social sciences, natural sciences, and medicine.

Feedback mechanisms in the atmosphere, hydrosphere, biosphere, and anthroposphere were studied under IMPETUS to better understand complex interactions leading to deteriorations in fresh water supplies in West and Northwest Africa. The aim was to identify the steering natural and anthropogenic factors (driving forces) that affect the water cycle, to establish an understanding of the underlying processes, and to assess the extent of their impacts.

Key findings on the basic subjects are presented in Part I of the book, entitled, "Fundamentals and process understanding". Part I begins by providing a detailed overview of the regional impacts of Global Change and of the regional geography. The scarcity of hydro-meteorological and vegetation data for the considered catchments necessitated the design of a customized measurement concept, which is described subsequently. Thereafter, the scientific background of the process understanding, together with the identification of driving forces are provided for the atmosphere, hydrosphere, biosphere, and anthroposphere. Part I forms the basis for Part II of the book, entitled, "Future projections and decision support". Part II focuses on findings surrounding the decision support with regard to future impacts of Global Change on the two catchments. Results are based on special climate and socio-economic scenarios.





2 Impacts of Global Change

2.1 Impacts of Global Change south of the Sahara
2.2 Impacts of Global Change north of the Sahara

I-2 Impacts of Global Change

A. H. Fink and M. Christoph

Keywords: Global Change, environmental change, globalization, demographic changes, Climate Change, land use change, biomass, biodiversity, land degradation, water availability

As previously mentioned in chapter I-1, Global Change is generally considered to consist of three components: demographic change, global environmental change, and the impacts of globalization. Strong population growth and migration are particular aspects of the ongoing Global Change in Africa. The present population growth in Africa, for example, is 2.32% p. a., compared to a worldwide increase of 1.24% p. a. between 2000 and 2005.

With respect to environmental change, climate variability and Climate Change, land use and land cover change, water availability, and the loss of biodiversity are pertinent issues for Africa. One important natural resource in Africa that is under stress is fresh water. Water is essential, not only for drinking, but for subsistence and commercial farming, for fisheries, livestock production, industry, mining, ecosystems, and hydropower, among others (DEWA 2006). Water availability is influenced by the hydrological cycle, which links the atmosphere, pedosphere, biosphere, and anthroposphere. The spatial and temporal variability of water resources is especially high in Africa, and it is directly linked to climate variability and population density. Furthermore, increasing population puts high pressure on other natural resources, like arable land and forests, which are already scarce in some regions of Africa. Not only does the available land for agriculture, animal husbandry, and forestry shrink per capita, the land also often reduces its capacity to produce food and materials. This is associated with a loss of biomass and biodiversity. This latter process is called land degradation, and about 31% of Africa's pasture land and 19% of its forests and woodlands are classified as degraded (UNEP 2008).

Africa has been impacted by the effects of globalization. A prominent example is the various trade barriers that would allow African countries to export cash crops to world markets. As will be argued below, economic globalization also has the potential to allow African countries to participate in the technological and financial innovations originating from industrial and emerging economies. In the following sections I-2.1 and I-2.2, the impacts of Global Change in tropical West Africa and Northwest Africa, respectively, will be discussed.

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References

DEWA – Division of Early Warning and Assessment of the UNEP (2006) AEO – African Environment Outlook 2 – our environment, our wealth. Nairobi

UNEP (2008) Africa – Atlas of our changing environment. United Nations Environment Programme, Nairobi http://na.unep.net/atlas/AfricaAtlas/. Accessed 12 November 2009

I-2.1 Impacts of Global Change south of the Sahara

A. H. Fink, M. Christoph, V. Ermert, A. Kuhn, T. Heckelei, and B. Diekkrüger

Abstract

A short overview is given of the strong population dynamics of West Africa, including urbanization and migration, the degree of water scarcity, and the effects of rainfall variability on hydropower generation. Climate-related diseases, like malaria and meningitis, as well as water-borne diseases like diarrhea, are also elaborated. Finally, the economic challenges imposed by climate, demographic growth, and globalization are outlined.

Keywords: Population growth, urban growth, climate variability, land degradation, deforestation, desertification, hydropower, malaria, diarrhea, Rift Valley fever, meningitis, water availability, water stress, water scarcity

Tropical West Africa is characterized by a large natural climate variability and high population dynamics. West Africa presently belongs among the regions with the highest population growth worldwide, exceeding 3% p. a. in several countries, including Benin (see also Heldmann and Doevenspeck 2008a). According to estimations by the United Nations (UN), the total population of all West African countries will almost double from about 240 million to over 400 million between the years 2000 and 2025 (UN 2009). It is expected that this development will be associated with the highest rate of urban growth in the world for the next decades (UNFPA 2007). The decline in the fraction of rural to total population and the increase in the numbers and sizes of cities in West Africa are depicted in figure I-2.1.1. West Africa is also characterized by corresponding strong migration flows. About 3% of the total West African population migrated in the year 2000 (see fig. I-2.1.2). The largest fraction of this migration, by far, was intra-regional, i.e., it occurred between West African nations (see fig. I-2.1.2). The reasons for migration are manifold, among which are labor migration, refuge from war and climate deterioration, and shortage of arable land. Only about 10% of the migrants left the West African sub-continent toward Europe and North America (see fig. I-2.1.2). This latter percentage is expected to increase in the coming decades.

In West Africa, deforestation, a major process of land degradation (see preface to chapter I-2), mainly occurs in the coastal countries. Here, the conversion of forests into farmland and for settlements, charcoal production, and logging activities are the major causes of deforestation. Between the years 2000 and 2005, annual deforestation rates in Ghana, Togo, Benin, and Nigeria exceeded 1.5%, about twice

as much as for the entire African continent (UNEP 2008). In the Sahel, overgrazing (see fig. I-2.2.1) and periodic droughts reduce the vegetation cover, thereby increasing soil erosion by water and wind. This second land degradation process is often called desertification.

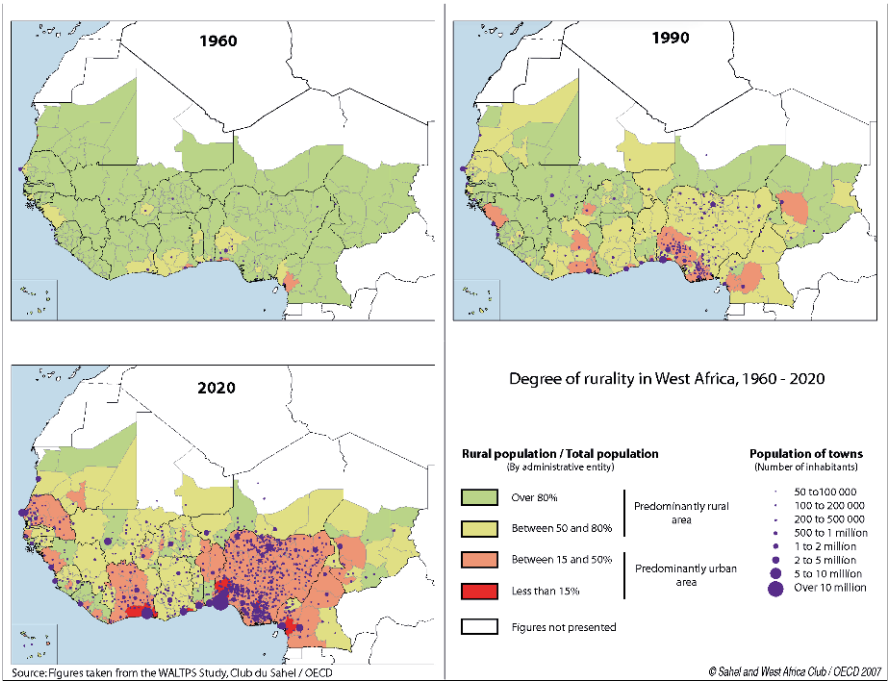

Fig. I-2.1.1: Change in the fraction of rural to total population and increase in number and size of cities: (a) 1960, (b) 1990, and (c) 2020 (Source: ECOWAS-SWAC/OECD 2006).

Water resources are under increasing pressure in sub-Saharan Africa, which is due even more to population development than to Climate Change. Water availability is often calculated per capita with a threshold of 1,700 m^3/capita/a as water stress. increase (see fig. I-2.1.3). In the future, increasing water abstraction will cause problems for downstream riparian communities and ecosystems, not only at the national, but also the trans-boundary scale. As an example, Lake Chad has dramatically decreased in size since the 1960s by more than 90% due to human water abstraction and Climate Change (Batello et al. 2004). This has caused tremendous effects on living conditions at the lake, like fishing and farming, and it has endangered the ecosystem. Global Change will further enhance these problems, and a solution requires trans-boundary basin management strategies. Both water quantity and quality are deteriorating. Poor land use practices have resulted in salinization, pollution of rivers, and sedimentation.

In West Africa, water use for irrigation and industrial purposes is generally very low. However, the use of surface water for hydropower generation, the most important energy source in the region, is quite substantial. The most important hydroelectric dams are the Lake Volta (Agbosombo) Dam in Ghana, the Mono Lake Dam in Togo, and the Kainji Dam in Nigeria. In the recent past, a series of 'drier-than-normal' years have caused power shortages in the large cities along the Guinea coast. For example, long lasting power outages occurred in Cotonou (Benin) in 1998 and in Accra (Ghana) in 2007. Presently, several new hydropower plants are planned or even already under construction along the Volta, Niger, and Ouémé rivers, which also influence downstream communities and ecosystems. Thus, it is reasonable to assume that the susceptibility of electric power supply in West Africa to rainfall alterations will remain in the decades to come. Another example of vulnerability to climate is the drought in the Sahel during the late 20th century. In combination with population growth, the drought was associated with profound impacts on the local population and on economics (Benson and Clay 1998; DEWA 2006). While the low amount of annual rainfall and its strong interannual variability in

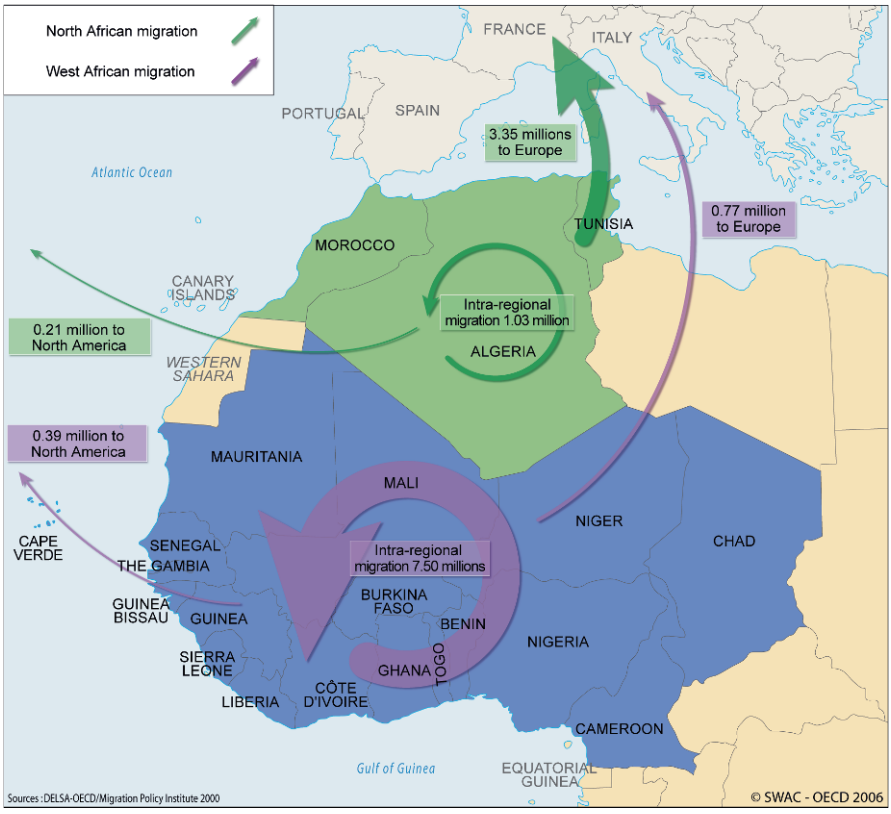

Fig. I-2.1.2: Intra-regional and extra-continental migrations in West and Northwest Africa for the year 2000 (Source: ECOWAS-SWAC/OECD 2006).

the Sahel (see sect. I-3.4) makes the region susceptible to increasing water stress, an insufficient supply of hygienically safe drinking water is also observed in several more humid countries in the Guinea coast region. In Benin, for example, the majority of the population in the northern and central parts has no access to safe potable water (Heldmann and Doevenspeck 2008b).

The latter problem is associated with a high prevalence of water-borne diseases like diarrhea. Diarrheal diseases are the third most important 'non-neonatal' cause of death among children under five years in Benin, being responsible for about 1/5 of infant mortality (WHO 2006). The most important cause of death is malaria. According to the World Malaria Report 2008 (WHO 2008), in 2006 malaria accounted for about 610,000 to 1,212,000 deaths worldwide, of which 90% were found in tropical Africa. Here, about 88% of deaths occurred among children under five years. Five West African countries, viz. Nigeria, Niger, Burkina Faso, Ghana, and Mali, ranked among the ten most affected African countries. The northern limit of malaria transmission in West Africa is the Sahelian zone, where rainfall limits the spread

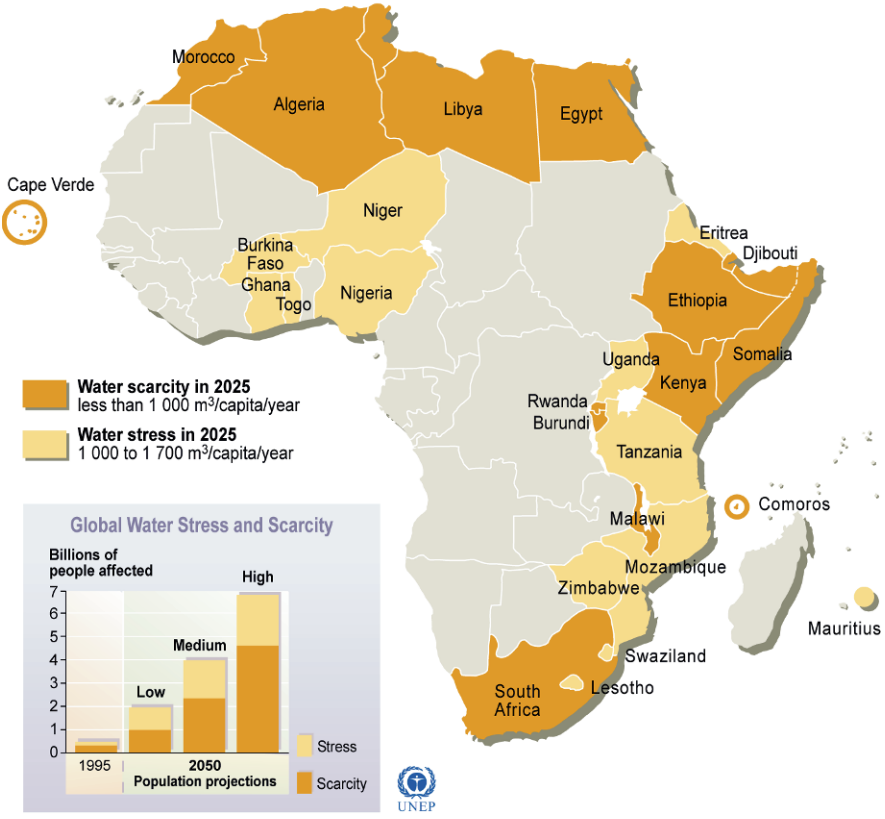

Fig. I-2.1.3: Projected fresh water stress and scarcity by 2025 (Source: UNEP/GRID-Arendal 2009).

of mosquitoes and, consequently, the spread of malaria (e.g., Ndiaye et al. 2001). The Sahelian drought since the 1970s, for example, has led to a decrease in malaria transmission in Senegal and Niger (Mouchet et al. 1996; Julvez et al. 1997b). In such areas, rainfall is a limiting factor for *Anopheles funestus*, which is one of the main malaria vector populations (e.g., Faye et al 1995; Julvez et al. 1997a, b). However, environmental changes that are mainly due to the development of irrigation systems have created favorable conditions for the reestablishment of *Anopheles funestus* in Senegal (Konaté et al. 2001).

Another vector-borne disease that depends on climate conditions is Rift Valley fever (RVF). RVF outbreaks are commonly correlated with periods of widespread and heavy rainfall (e.g., Meegan and Bailey 1988). It is assumed that ecologically, weather conditions increase virus transmission and circulation. The first RVF epidemic in West Africa was reported in 1987 and was linked to the controlled flooding in the lower Senegal River area. The flooding altered the interaction between animals and humans, and it resulted in the transmission of the RVF virus to humans (CDC 2009).

Another disease strongly affected by climate conditions is meningococcal meningitis. Countries within the 'Meningitis Belt' in semi-arid sub-Saharan Africa experience the highest endemicity and epidemic frequency of meningococcal meningitis in Africa (e.g., Molesworth et al. 2002). The spatial distribution, intensity and seasonality of meningococcal (epidemic) meningitis appear to be strongly linked to climatic and environmental factors, particularly drought, although the causal mechanism is not clearly understood (e.g., Molesworth et al. 2001). The geographical distribution of meningitis has expanded in West Africa in recent years. This may be attributable to environmental change, driven by both changes in land use and regional Climate Change (Molesworth et al. 2003).

There is a growing consensus that Global Change will also pose a particular challenge for sub-Saharan Africa regarding agriculture and food security. Fischer et al. (2005) estimate that cereal yields due to Climate Change might decline by 15% by the year 2080 accompanied by an expansion of arid lands in Africa by 8%. Consequently, cereal production per capita might decrease by a range of 3.9-7.5% (Tubiello and Fischer 2007). Agricultural Gross Domestic Product (GDP) might fall by as much as 20% in developing countries, while only dropping by 6% in industrial countries (Cline 2007). Battisti and Naylor (2009) point out that in addition to changing precipitation patterns, rising temperatures in the tropics and subtropics might have a yield-depressing effect between 2.5 and 16% per 1°C increase. As to the market effects of rising temperatures, Easterling et al. (2007) estimate that an increase in average temperatures of 3°C may cause agricultural prices to rise up to 40%. This would negatively affect the net food importers among sub-Saharan African countries (i.e., the majority). Even though such considerable price increases would clearly provide strong incentives to African farmers to expand production, the question remains whether their supply adjustment would be significant and how such an adjustment might be achieved. Currently, increasing food scarcity in Africa due to population growth is mainly addressed by expanding cropland, while increases

in productivity through the use of advanced farming systems and inputs are limited.

Due to the rapid population growth outlined above and the ensuing scarcity of land and water resources, adapting the agricultural sector to Global Change will remain a difficult task for African decision makers from the local up to the international level. Two sides of the problem exist: on the one hand, the biophysical scope of adaptation in farm production will diminish when temperatures during the growing seasons reach a magnitude where the cultivation of food crops becomes physiologically difficult. The interplay of Climate Change and degraded soils will make an 'African Green Revolution' hard to achieve (Evenson and Gollin 2003). On the other hand, sub-Saharan Africa's institutional and economic capacity for adaptation is very restricted. Widespread and severe poverty, particularly in rural areas, limits the possibilities for small farmers to invest in coping with Climate Change. On the regional and national scale, governance problems originating from corruption, ethnic divisions and wars, a lack of administrative capacity, and continuing addiction to foreign aid have so far prevented most sub-Saharan African countries from repeating the East-Asian success stories (Easterly and Levine 1997). Adaptation will require substantial investments in new technologies and human capacity to mitigate the consequences of Global Change. Most African countries are too poor to sustain, for instance, subsidies on input or credit to quickly boost their agricultural production (see, e.g., Carr (1997) on the failed Green Revolution in Malawi). In this context, the recent 'Alliance for a Green Revolution in Africa' (AGRA[1]) initiative is a promising, African-led approach that particularly aims at increasing the productivity of small-scale farming.

Other aspects of Global Change may actually help sub-Saharan Africa to adapt to Climate Change. Economic globalization, being an integration of national economies into the international economy through trade, foreign direct investment, capital flows, migration, and the spread of technology (Bhagwati 2004), has the potential to let African countries participate in the technological and financial innovations originating from industrial and emerging economies. For instance, there are numerous examples that open trade regimes, both on the part of exporters and importers, can tremendously help to avoid famines that result from failed harvests (von Braun 2007). The most recent price hike in world grain markets was not only caused by drought in Australia, but also by export taxes or bans by Argentina, Thailand or India targeted at increasing tax revenues and keeping domestic prices down. Moreover, foreign investment in Africa's agricultural sectors is on the rise. These investments could be further strengthened if governments would be committed to securing investors' property rights and to finding tax and redistribution schemes that create sufficient returns for potential investors and allow for participation by the local population. Technologies that were unavailable to Africa and Europe two centuries ago can now be transferred from industrial countries, but Africa would not have to provide the huge investments for research and develop-

[1] www.agra-alliance.org

ment, as these have been covered by the industrial countries. Therefore, Global Change in the form of economic integration can be seen as an opportunity for Africa to mitigate the ecological consequences of Global Change.

References

Batello C, Marzot M, Touré AH (2004) The future is an ancient lake. FAO, Rome

Battisti DS, Naylor RL (2009) Historical Warnings of Future Food Insecurity with Unprecedented Seasonal Heat. Science 323:240-244

Benson C, Clay EJ (1998) The impact of drought on sub-Saharan economies. World Bank Tech Paper, 401. Wold Bank, Washington DC

Bhagwati J (2004) In Defense of Globalization. Oxford University Press, New York

Carr SJ (1997) A green revolution frustrated: lessons from the Malawi experience. Afr Crop Sci J 5:93-98

CDC – Centers for Disease Control and Prevention (2009) Centers for Disease Control and Prevention – Your Online Source for Credible Health Information. http://www.cdc.gov. Accessed 24 November 2009

Cline WR (2007) Global Warming and Agriculture – Impact Estimates by Country. Center for Global Development, Washington DC

DEWA – Division of Early Warning and Assessment of the UNEP (2006) AEO – African Environment Outlook 2 – our environment, our wealth. Nairobi

Easterling WE, Aggarwal PK, Batima P, Brander KM, Erda L, Howden SM, Kirilenko A, Morton J, Soussana J-F, Schmidhuber J, Tubiello N (2007) Food, fibre and forest products. In: IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press, Cambridge, UK

Easterly W, Levine R (1997) Africa's Growth Tragedy: Policies and Ethnic Divisions. Q J Econ 112:1203-1250

ECOWAS (Economic Community of West African States)-SWAC (Sahel and West African Club)/OECD (Organisation for Economic Cooperation and Development) (2006) The Web Atlas on Regional Integration in West Africa. http://www.atlas-ouestafrique.org/spip.php?rubrique36. Accessed 24 November 2009

Evenson RE, Gollin D (2003) Assessing the Impact of the Green Revolution, 1960 to 2000. Science 300:758

Faye O, Gaye O, Fontenille D, Hebrard G, Konaté L, Sy N, Hervé J-P, Touré Y, Diallo S, Molez J-F, Mouchet J (1995) La sécheresse et la baisse du paludisme dans les Niayes du Sénégal. Cahiers Santé 5:299-305

Fischer G, Shah M, Tubiello F, van Velhuizen H (2005) Socio-economic and climate change impacts on agriculture: An integrated assessment, 1990-2080. Philos T R Soc B 360:2067-2083

Heldmann M, Doevenspeck M (2008a) Demography: Spatial Disparities and High Growth Rates. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 103-104. Department of Geography, University of Bonn, Bonn

Heldmann M, Doevenspeck M (2008b) DrinkingWater Supply in Benin. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 43-44. Department of Geography, University of Bonn, Bonn

Julvez J, Mouchet J, Michault A, Fouta A, Hamidine M (1997a) Eco-épidémiologie du paludisme à Niamey et dans la vallée du fleuve, République du Niger, 1992-1995. B Soc Pathol Exot 90:94-100

Julvez J, Mouchet J, Michault A, Fouta A, Hamidine M (1997b) Evolution du paludisme dans l'est sahélien du Niger. Une zone écologiquement sinistrée. B Soc Pathol Exot 90:101-104
Konaté L, Diop A, Sy N, Faye MN, Deng Y, Izri A, Faye O, Mouchet J (2001) Comeback of Anopheles funestus in Sahelian Senegal. Lancet 358:336
Meegan JM, Bailey CL (1988) Rift Valley fever. In: Monath TP (ed) The arboviruses: epidemiology and ecology. Volume 4, pp. 61-76. CRC Press, Boca Raton, FL
Mouchet J, Faye O, Julvez J, Manguin S (1996) Drought and malaria retreat in the Sahel, West Africa. Lancet 348:1735-1736
Molesworth AM, Djingary MH, Thomson MC (2001) Seasonality in meningococcal disease in Niger, West Africa: a preliminary investigation. In: Flahaut A, Toubiana L, Valleron A-J (eds) Geography and medicine: GEOMED'99, pp. 92-97. Elsevier, Paris
Molesworth AM, Cuevas LE, Morse AP, Herman JR, Thomson MC (2002) Dust clouds and spread of infection. Lancet 359:81-82
Molesworth AM, Cuevas LE, Connor SJ, Morse AP, Thomson MC (2003) Environmental Risk and Meningitis Epidemics in Africa. Emerg Infect Dis 9:1287-1293
Ndiaye O, Le Hesran Y-L, Etard J-F, Diallo A, Simondon F, Ward MN, Robert V (2001) Variations climatique et mortalité attribuée au paludisme dans la zone de Niakhar, Sénégal, de 1984 à 1996. Santé 11:25-33
Tubiello FN, Fischer G (2007) Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000-2080.Technol Forecast Soc 74:1030-1056
UN (2009) World Population Prospects: The 2008 Revision Population Database. http://esa.un.org/unpp. Accessed 27 October 2009
UNFPA – United Nations Population Fund (2007) State of world population 2007 Unleashing the Potential of Urban Growth. UNFPA, New York http://www.unfpa.org/upload/lib_pub_file/695_filename_sowp2007_eng.pdf. Accessed 21 January 2010
UNEP – United Nations Environment Programme (2008) Africa – Atlas of our changing environment. United Nations Environment Programme, Nairobi. http://na.unep.net/atlas/AfricaAtlas. Accessed 24 November 2009
UNEP/GRID (Global Resource Information Database)-Arendal (2009) Freshwater stress and scarcity in Africa by 2025. UNEP/GRID-Arendal Maps and Graphics Library, 2002. http://maps.grida.no/go/graphic/freshwater_stress_and_scarcity_in_africa_by_2025. Accessed 11 May 2009
von Braun J (2007) The world food situation: new driving forces and required actions. IFPRI Food Policy Report No 18, Washington DC
WHO – World Health Organisation (2006) WHO – Country Mortality Fact Sheet 2006. http://www.who.int/whosis/mort/profiles/mort_afro_ben_benin.pdf. Accessed 25 November 2009
WHO (2008) World Malaria Report 2008. Geneva. http://apps.who.int/malaria/wmr2008/malaria2008.pdf. Accessed 24 November 2009

I-2.2 Impacts of Global Change north of the Sahara

A. H. Fink, M. Christoph, B. Diekkrüger, B. Reichert, A. Kuhn, and T. Heckelei

Abstract

A brief overview is given of future climate projections and population dynamics and their potential consequences on the development of freshwater availability for Northwest Africa. Some potential socio-economic impacts of Climate Change and demographic changes are discussed.

Keywords: Afforestation, deforestation, freshwater availability, groundwater, irrigation, land degradation, Maghreb, migration, overgrazing, population, soil erosion, salinization, surface water, sustainable development, water exploitation index, urbanization, water demand, evapotranspiration

Like West Africa, Northwest Africa has experienced large natural fluctuations in precipitation. The region north of the Atlas Mountains has exhibited a decadal precipitation decline commencing in the 1970s, which is simultaneous with the Sahel (see later sect. I-3.4). In contrast to the West African region, the population growth in the Maghreb is only moderate, i.e., 1.5% p.a. (UNDP 2006). Another difference pertains to the target regions of migration. As can be seen in figure I-2.1.2, more than three times as many migrants move to Europe and North America compared to intra-regional movements. In total, a fraction of about 6% of the Maghrebian population migrated, which is twice as much as for West Africa (see sect. I-2.1). The primary motivation of the migrants is the search for labor to support their families, who often remain in the villages.

The moderate population growth, extensive irrigation-fed cash crop cultivation, overstocking of herds, and a large, natural year-to-year variability of precipitation aggravates the already existing scarcity of natural resources. Overgrazing, as a consequence of the overstocking of sheep and goat herds, reduces the vegetation cover as well as the forest area in the Atlas Mountains (see fig. I-2.2.1). This in turn enhances soil erosion after heavy rainfall events. Deforestation in the Maghrebian countries of Morocco, Algeria, and Tunisia has already occurred during historical times. Presently, the forest area is increasing due to afforestation programs (UNEP 2008). Another important process of land degradation in the Maghreb is the salinization of soils as a consequence of intensive irrigation that uses groundwater resources due to the scarcity of surface irrigation water. As evident in figure I-2.2.2, salinization causes problems in the river oases south of the Atlas chain, as well as

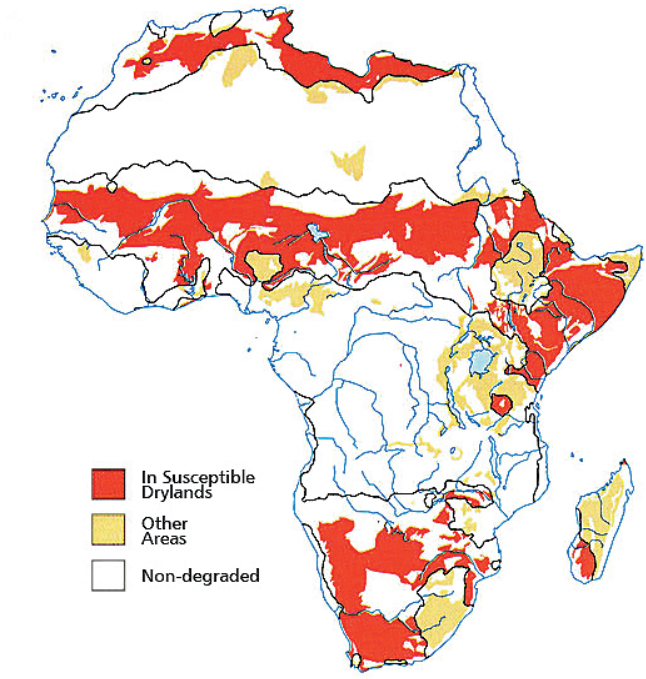

Fig. I-2.2.1: Areas affected by overgrazing (Source: UNEP/ISRIC and CRU/UEA 2005).

in many river catchments draining toward the Atlantic Ocean and the Mediterranean Sea. These latter catchments are often prone to extensive cultivation of cash crops, some of which have a high water demand.

According to the FAO (2005), Morocco has a freshwater availability of 934 m^3/a/capita. Freshwater availability is 443 m^3/a/capita and 459 m^3/a/capita for Algeria and Tunisia, respectively. With these figures, these countries are already now below the critical threshold of 1,000 m^3/a/capita for sustainable development. Even without the effects of Climate Change, freshwater availability will decrease to 700 m^3/a/capita, 350 m^3/a/capita, and 300 m^3/a/capita for Morocco, Algeria, and Tunisia, respectively (Sansavini 2002) by 2025 due to population growth. The water exploitation index for these countries is already above 50% (Boko et al. 2007). This indicator measures the relative pressure of annual withdrawals on conventional renewable natural freshwater resources, including transport losses. According to the Regional Model (REMO) results obtained within IMPETUS, the temperature in the Maghreb will increase between 2 and 3°C by 2050, and precipitation is likely to decrease between 10% and 20%. These climate projections are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A1B climate scenario (Paeth et al. 2009). This will result in an increase in potential evapotranspiration as well as a significant decrease in groundwater recharge and discharge. Another scenario calculation shows

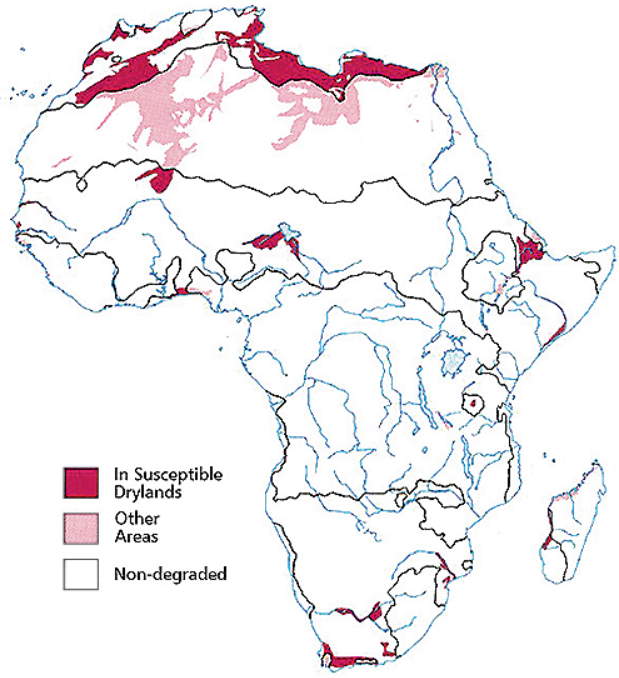

Fig. I-2.2.2: Areas affected by salinization (Source: UNEP/ISRIC and CRU/UEA 2005).

an increase in temperature by 1°C for the Quergha Basin in Morocco and a precipitation reduction similar to REMO, thereby reducing discharge by 10% (Agoumi 2003). Lower river discharge causes a reduced dilution effect concerning water pollution, and the increase in temperature influences bio-chemical processes in the river system in addition to affecting hydro-ecology. Furthermore, reduced discharge may result in limited reservoir filling levels while simultaneous evaporation losses increase due to temperature increase. Another factor reducing the capacity of reservoirs is the siltation process, the intensity of which depends on upstream erosion rates. An increase in evapotranspiration and a decrease in rainfall cause an increase in irrigation agriculture as rain-fed agriculture is restricted. This is further aggravated by an increasing demand in agricultural products.

Due to limited surface water availability, reduced groundwater recharge and growing water demand due to irrigation requirements, groundwater resources are increasingly under pressure. As an example, the water table of the Souss aquifer in Morocco has decreased by 40 m during the last decade (Ben Abdelfadel and Driouech 2008). Overexploitation of groundwater resources also causes saltwater intrusion at the coast and deteriorates groundwater quality (Agoumi 2003). Reduced groundwater recharge reduces the dilution effect concerning salts, agro-chemicals, and sewage. Therefore, not only water quantity, but also water quality, will decline in future.

All three Maghreb countries face consequences of Global Change, mainly in the form of economic globalization and Climate Change. When these external driving forces combine with internal trends, such as demographic developments and a declining availability of natural resources, a characteristic pattern of economic challenges arises.

The population of the Maghreb countries adds up to 70 million, and it is still growing at 1.5 percent per year (UNDP 2006). At these growth rates, it is expected that the region will be inhabited by almost 99 million people in 2025 (CIHEAM 2007). One-third of the population is below the age of fifteen. Creating educational and employment opportunities for these younger cohorts will be a major task for economic policy. Official statistics estimate the unemployment rates to be between 11% in Morocco and 15% in Algeria (ILO 2004). Unemployment and, even more importantly, underemployment cause widespread poverty, migration pressure, and social unrest (Houdret et al. 2008).

Despite the fact that roughly a quarter of the working population is still employed in the farming sector and in food processing, the Maghreb countries are also characterized by rapid urbanization (CIHEAM 2007). The urban population share is estimated to increase to 70% by 2015. For the development of water infrastructure, this presents a difficult task. While heavy investment will be necessary in urban environments, the need for such investments in rural areas that are prone to depopulation is much more difficult to assess and more expensive to implement.

The economic impact of Climate Change on these countries will be dominated by the effects on farm production. As quantified above, a significant temperature increase and precipitation decrease is projected by REMO under the A1B IPCC SRES scenario. Contrary to the West African precipitation changes, these trends are quite robust among the 21 global climate models in the IPCC report (Christensen et al. 2007). As these countries are already located in hot climates, the effect on agricultural production will most likely be negative. Production portfolios may have to change, and the need to raise area productivity and the efficiency of irrigation water use will become more pressing.

The potential of the Maghreb countries to cope with Climate Change and adapt to new requirements will crucially depend on their economic relations with Europe and emerging economies such as China and India. The Maghreb countries are too small and too scarce in land and water resources to make policies of self-sufficiency in agriculture an option. Globalization in the form of trade liberalization and economic integration has indeed made considerable progress since the 1990s. The MEDA (*MEsures D'Accompagnement*, the main financial instrument of the Euro-Mediterranean partnership) Program, in cooperation with the European Union (EU), is the most important example for cooperation in trade and investment (Houdret et al. 2008). It involves investment aid of 12.3 billion € in the new millennium and a successive removal of barriers to trade in 2008-2012 (EIB 2006). Farm products, unfortunately, are largely exempt from liberalization, which is detrimental to the interests of both producers and consumers in the Maghreb countries.

References

Agoumi A (2003) Vulnerability of North African countries climate change. Adaptation and implementation strategies for climate change. IIDS (2003): International Institute for Sustainable Development – Climate Change Knowledge Network. http://www.cckn.net/pdf/north_africa.pdf. Accessed 18 November 2009

Ben Abdelfadel A, Driouech F (2008) Climate Change and its impact on water resources in the Maghreb region. http://portal.worldwaterforum5.org/wwf5/en-us/worldregions/mena%20arab%20region/consultation%20library/climat%20change%20and%20impact%20on%20wr%20in%20maghreb.doc. Accessed 18 November 2009

Boko M, Niang I, Nyong A, Vogel C, Githeko A, Medany M, Osman Elasha B, Tabo R, Yanda P (2007) Africa. In: IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 433-467. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press, Cambridge, UK

CIHEAM – Centre International des Hautes Études Agronomiques Méditerranéennes (2006) Observatoire Méditerranéen – profil pays – Algérie, Maroc, Tunisie. http://ressources.ciheam.org/observatoire/panorama/medobsexterne/defindics.php. Accessed 17 November 2009

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon WT, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P´(2007) Regional Climate Projections. In: IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

EIB – European Investment Bank (2006) Annual Report 2006, Part 3, Statistics. http://www.EIB.org/about/publications/annual-report-2006.htm. Accessed 18 November 2009

FAO – Food and Agriculture Organisation (2005) Freshwater Resources. http://earthtrends.wri.org/pdf_library/data_tables/wat2_2005.pdf. Accessed 18 November 2009

Houdret A, Kievelitz U, Mumenthaler M (2008) Die Zukunft des Maghreb: Trends in Sicherheit und Entwicklung in Marokko, Algerien und Tunesien. Duisburg: Institut für Entwicklung und Frieden, Universität Duisburg-Essen, http://inef.uni-due.de/page/documents/Houdret_Maghreb.pdf. Accessed 18 November 2009

ILO – International Labour Organisation (2004) Yearly Data – Algeria, Morocco, Tunisia. http://laborsta.ilo.org. Accessed 18 November 2009

Paeth H, Born K, Girmes R, Podzun R, Jacob D (2009) Regional climate change in tropical and northern Africa due to greenhouse forcing and land-use changes. J Climate 22:114-132

Sansavini S (2002) Water And Irrigation on the Mediterranean's southern rim: A vital factor for its people and horticulture. Acta Hortic (ISHS) 582:53-65 http://www.actahort.org/books/582/582_3.htm. Accessed 18 November 2009

UNDP – United Nations Development Programme (2006) Data – Algeria, Morocco, Tunisia. http://hdrstats.undp.org/countries. Accessed 18 November 2009

UNEP/ISRIC – United Nations Environment Programme/International Soil Reference and Information Centre – and CRU/UEA – Climate Research Unit/University of East Anglia (2005) Properties and Management of drylands. Maps of drylands and desertification – Africa. http://www.fao.org/ag/agl/agll/drylands/mapsafrica.htm. Accessed 24 November 2009

UNEP – United Nations Environment Programme (2008) Africa – Atlas of our changing environment. Nairobi. http://na.unep.net/atlas/AfricaAtlas/. Accessed 18 November 2009





3 Regional geography of West and Northwest Africa: An introduction

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3.2 Topography and natural regions

3.3 Soils

3.4 Climate

3.5 Hydrology

3.6 Flora and vegetation

3.7 Political and administrative structures: History and present situation

3.8 Population, ethnicity, and religion

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I-3 Regional geography of West and Northwest Africa: An introduction

G. Menz

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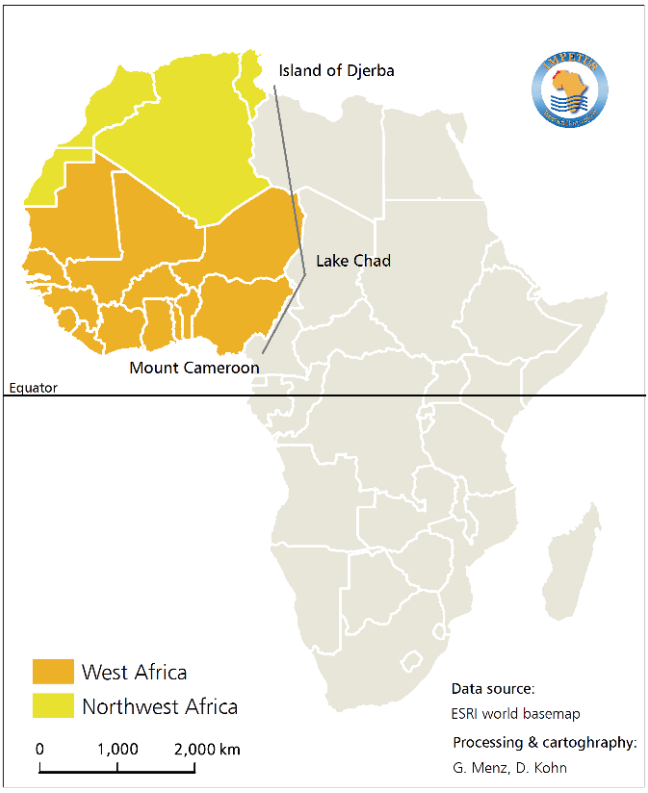

Fig. I-3.0.1: Location and delineation of West and Northwest Africa according to the United Nations Statistical Division (Source: Modified after United Nations Statistical Yearbook 2008).

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The two IMPETUS test sites – the Ouémé catchment in Benin and the Wadi Drâa in Morocco - belong to the broad geographical sub-regions of West and Northwest Africa. These sub-regions have been delineated for statistical purposes by the United Nations Statistical Division and do not reflect ecological or natural conditions. Both sub-regions are oriented west of an imagined south-north axis lying close to 10° east longitude (see fig. I-3.0.1). The Atlantic Ocean forms the western and southern borders, while the Mediterranean Sea is the border in the north. The eastern border is less precise, commonly it is placed on a virtual line running from Mount Cameroon in the south, through Lake Chad to the Island of Djerba in the north.

The current boundaries of West and Northwest African nations reflect colonial boundaries, cutting across natural, ethnic and cultural lines. Northwest Africa includes the nations of Morocco, Algeria, Tunisia, and Western Sahara. West Africa includes the nations of Benin, Burkina Faso, Ivory Coast, Cape Verde, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauretania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. Together, the two sub-regions occupy an area of more than 6,140,000 km² - approximately one fifth of Africa. The great majority of the land surface within the sub-regions consists of plains lying less than 300 meters above sea level, though there are isolated hills and mountain ranges in numerous countries (e.g., High Atlas Mountain in Morocco).

The countries of the Maghreb (Algeria, Morocco, Tunisia, and Western Sahara) and of the Sahel (Senegal, Mali, Burkina Faso, and Niger) are composed of semi-arid terrain. The Sudan zone (a transition zone between the Sahara and the savannahs of West Africa) is characterized by a sub-humid climate with several different dense tree-bush-grass vegetation formations. The humid Guinea climatic zone is found further south; it is a 180-240 km wide area containing intensive plantation agriculture.

The following material will provide a brief systematic overview of the wide variety of natural and cultural conditions within West and Northwest Africa. In addition, several important geographical characteristics specific to the two IMPETUS study sites in Benin and Morocco will be discussed in detail. This discussion is

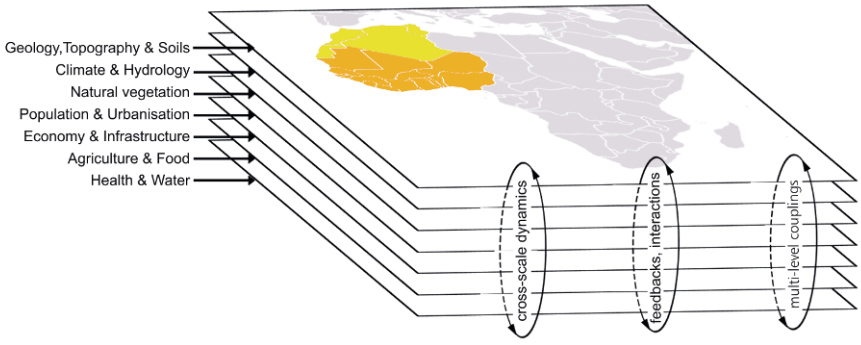

Fig. I-3.0.2: Layer concept after Alfred Hettner (Source: Gebhardt et al. 2007 after Hettner 1935).

based on Hettner's *Länderkundliche Schema*, or Layer Concept (Hettner 1935), a methodological concept widely used in environmental studies. The Layer Concept incorporates three types of data: 1) Abiotic or inorganic factors of geology, topography, climate, and hydrology; 2) Biotic or organic factors, including soil, natural vegetation, and agriculture; and 3) Cultural and socio-economic factors of economics, health, and politics (see fig. I-3.0.2). These cultural/socio-economic factors are often the result of complex interactions or feedbacks between the different layers.

I-3.1 Geology

B. Reichert, S. Klose, and A. Kocher

This section should be cited as: Reichert B, Klose S, Kocher A (2010) Geology. In: Speth P, Christoph M, Diekkrüger B (eds) Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Heidelberg, Germany

The record of West Africa and Northwest Africa traces a geological evolution of about 3,000 Ma (Piqué 2001; Michard et al. 2008). The geology of West Africa is predominantly characterized by the West African Craton (WAC), which is a stable and spacious unit that extends over an area 4,500,000 km² (see fig. I-3.1.1). The WAC comprises shields of an Archean-Paleoproterozoic lithosphere with granitoids, gneisses and metamorphic rocks 3,000 to 2,000 Ma old. It is surrounded by Pan-African belts (760 to 560 Ma) on its northern (e.g., the Moroccan Antiatlas) and southern margins (e.g., the Dahomeyides in Togo, Ghana and Benin) (Michard et al. 2008). At the northwestern rim, the WAC exhibits a complex, geodynamic evolution of alternating phases of continental building and breaking up. The southern part of the WAC has remained more or less stable for at least 1,700 to 1,000 Ma (Michard et al. 2008).

Both the Ouémé basin and the Drâa basin are situated on the WAC. As part of the stable margin of the WAC, the Ouémé basin is mainly characterized by a Precambrian basement. Only the southern region differs (from the 7th latitude to the coast), with sedimentary deposits of Cretaceous to recent age. The geological setting of the Drâa basin represents the northwestern rim of the WAC. It is very special in terms of its variety of witnesses to Earth history and to rock properties (Ennih and Liégeios 2008; Michard et al. 2008).

I-3.1.1 The Ouémé basin (southeastern edge of WAC)

Situated on the southeastern edge of the WAC, Benin's geology (and thus the Ouémé basin's) is dominated by the Dahomeyides, a Pan-African belt (see fig. I-3.1.1) (Affaton et al. 1991; Ennih and Liégeois 2008). Only 20% of Benin is occupied by younger sediment basins. These include a small part of the Cambrian Volta basin in the northeast, the Palaeozoic Kandi basin in the east and the Cretaceous to recent Coastal basin in the south, which is a part of a huge structural unit stretching from Ivory Coast to Nigeria (see fig. I-3.1.2) (Affaton et al. 1991).

The Precambrian consists predominantly of complex migmatites, granulites and gneisses, including less abundant mica shists, quartzites and amphibolites. Syn- and post-tectonic intrusions of mainly granites, diorites, gabbros and volcanic rocks are present (Wright and Burgess 1992).

Folding of the Precambrian formations is strong. The superposition of different tectonic phases results in an intense fracturing of the sequence, the development of major faults many kilometers in length (e.g., the NNE-SSW trending Kandi fault), and various grades of rock metamorphism (Bellion 1987). The thickness of the fractured zone is variable. Ultramylonite bands accompany many of the faults.

Three major tectonic events characterize the area of the Dahomeyides. The first event was the Pan-African orogen (500–670 Ma), in which the WAC collided with the East Saharan Craton and several micro-continents aggregated (Tidjani et al. 1997). The second event is connected with the opening of the Central Atlantic in the Triassic-Liassic (180–245 Ma), which led to a generally tensional regime accompanied by magmatic events in West Africa. The last major event was the

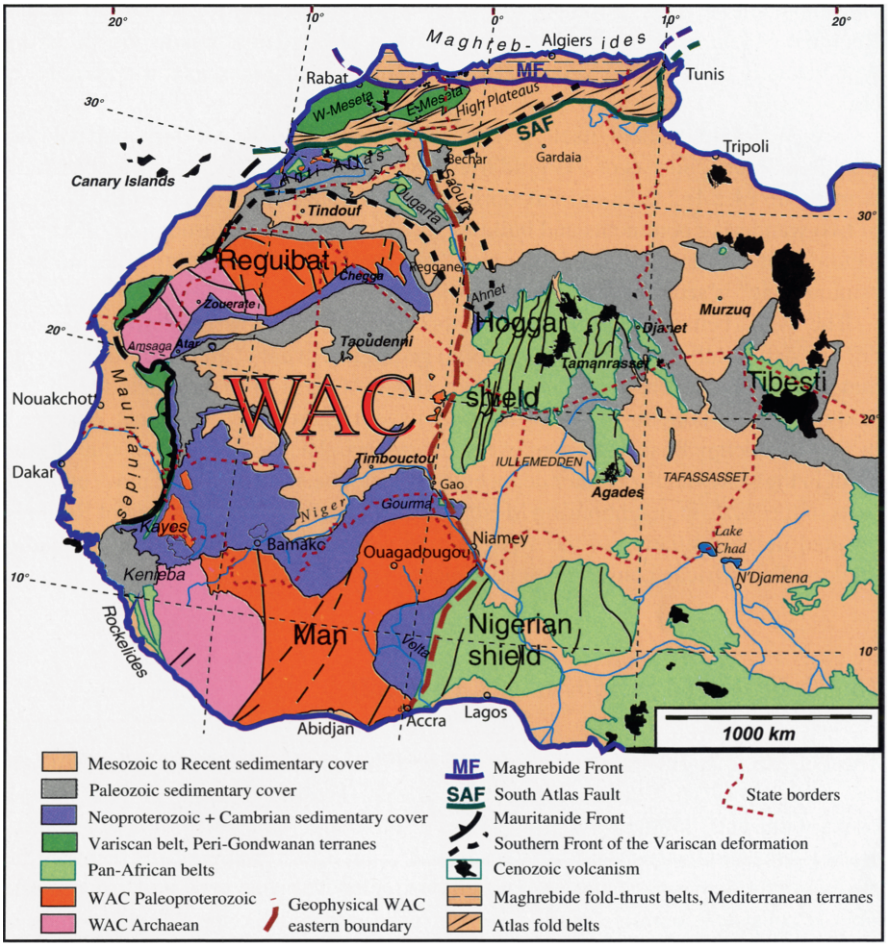

Fig. I-3.1.1: Structural map of Northwest Africa with the delineation of the West African Craton (WAC) (Source: Michard et al. 2008).

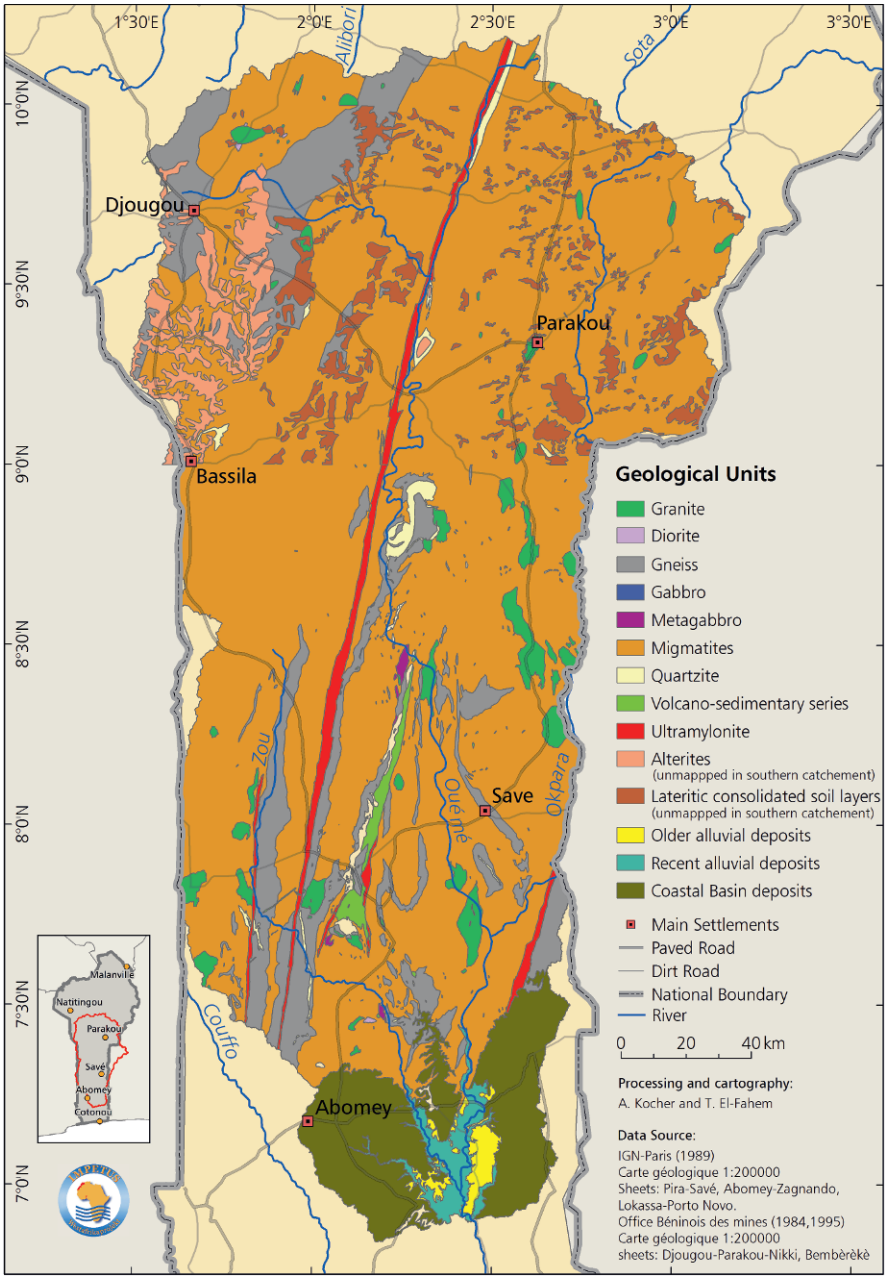

Fig. I-3.1.2: Geological map of the Ouémé catchment.

opening of the western Coastal basin in the lower Cretaceous (120 Ma). The Middle Eocene collision between Africa and Europe resulted in a slight reworking of the structural pattern and a reactivation of the Kandi fault (Bellion 1987).

At the beginning of the Cenozoic (65 Ma), a warm and humid climate dominated in West Africa. Under these climatic conditions, a physicochemical disaggregation of the magmatic and metamorphic rocks led to the development of the regolith as a heterogeneous alteration cover of various thickness on top of the crystalline basement (Taylor and Eggleton 2001). The regolith together with the fractured part of the basement form the main aquifer systems (Fass 2004; El-Fahem 2008).

I-3.1.2 The Drâa basin (northwestern edge of WAC)

The Drâa basin includes the southern flank of the Central High Atlas, the sedimentary Ouarzazate Basin and parts of the central and eastern Antiatlas. Two orogens, the High Atlas and the Antiatlas, are divided by an important tectonic lineament called the South Atlas Fault (SAF, see fig. I-3.1.1 and I-3.1.3) (Ennih and Liégeois 2008). The Antiatlas comprises a Proterozoic basement and a Palaeozoic cover affected by the Variscan orogen (Burkhard et al. 2006; Ismat 2008; Michard et al. 2008). The High Atlas is part of the Alpine orogen (Stets and Wurster 1981; Beauchamp et al. 1999; Michard et al. 2008). Climatic fluctuations have determined the latest geological history by cyclic sedimentation and erosion (Arboleya et al. 2008).

The Proterozoic basement consists of crystalline metamorphic rocks overlain by a moderately metamorphic volcano-sedimentary sequence intruded by granites. Palaeozoic sedimentary successions of mainly shallow marine origin cover the basement (Michard 1976; Choubert and Faure-Muret 1983; Collins and Pisarevsky 2005; Burkhard et al. 2006; Michard et al. 2008). Varying shallow marine to continental facies interbedded by basalts form the Mesozoic to Cenozoic record, which only occurs in the Central High Atlas and the Ouarzazate Basin (Michard 1976; Heinitz et al. 1986). A Tertiary and Quaternary molasse crops out in the foreland of the Ouarzazate Basin (Jossen and Filali 1988). Furthermore, alluvial and lacustrine deposits occur in smaller basins and as terraces along wadis (see fig. I-3.1.3 and sect. I-3.5; I-6.2).

The underground reveals a great variety of rocks according to the complexity of the geodynamic history. The resulting wide range of geochemical and geohydraulic properties determine soil formation and hydrologic phenomena. The weathering resistance of the crystalline rocks in the Antiatlas differs widely from the locally evaporite-bearing deposits in the High Atlas to the sedimentary basins (see sect. I-3.3). Hydraulic conductivities and storage capacities range from very low for the crystalline basement to very high for some alluvial deposits. The Mesozoic limestones in the High Atlas and the Quaternary porous media play an important role for hydrological and hydrogeological issues (see sect. I-6.2; e.g., Cappy 2006; Klose et al. 2008).

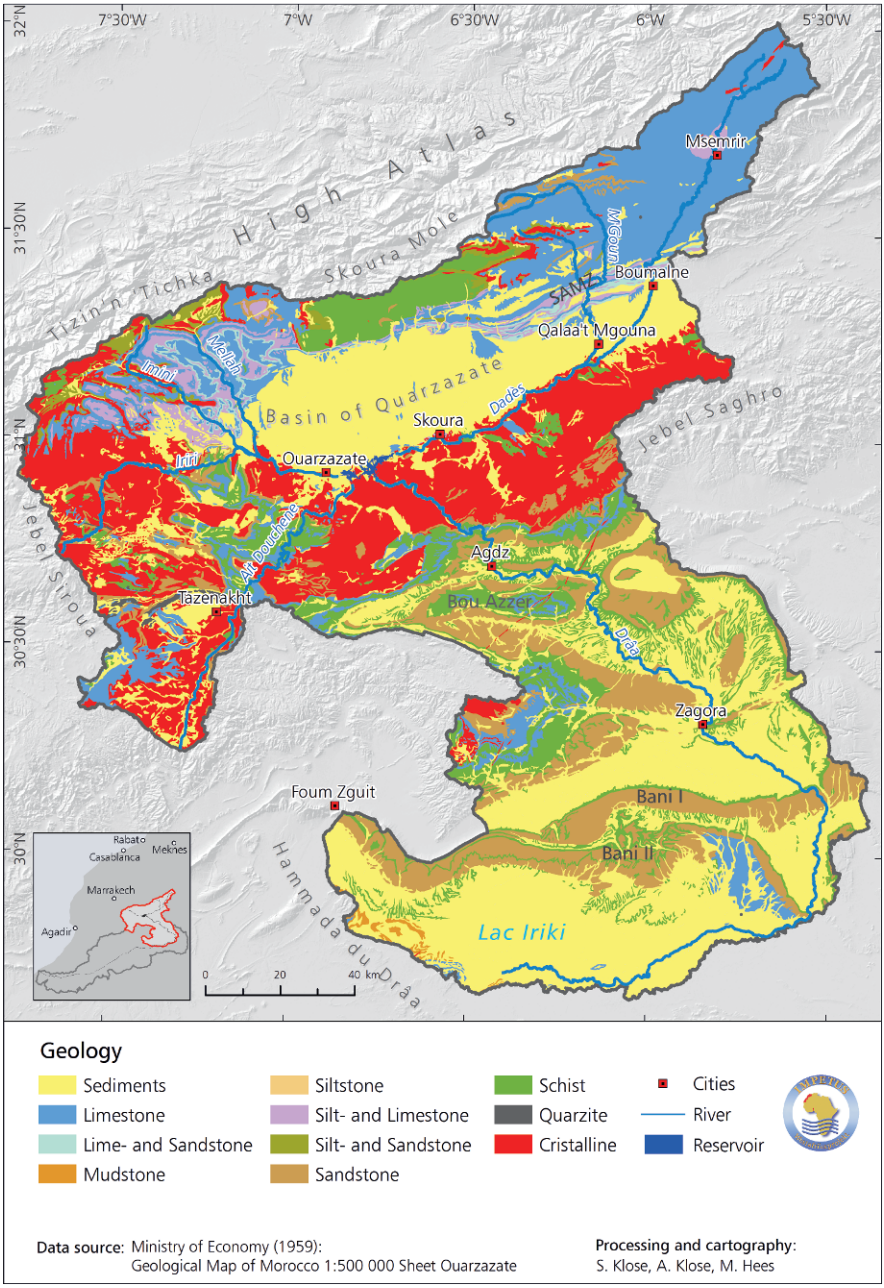

Fig. I-3.1.3: Geological map of the Upper and Middle Drâa catchment (Data source: Abdeljali et al., 1959: *Carte Géologique 1:500,000 – Feuille Ouarzazate*).

I-3.2 Topography and natural regions

G. Menz

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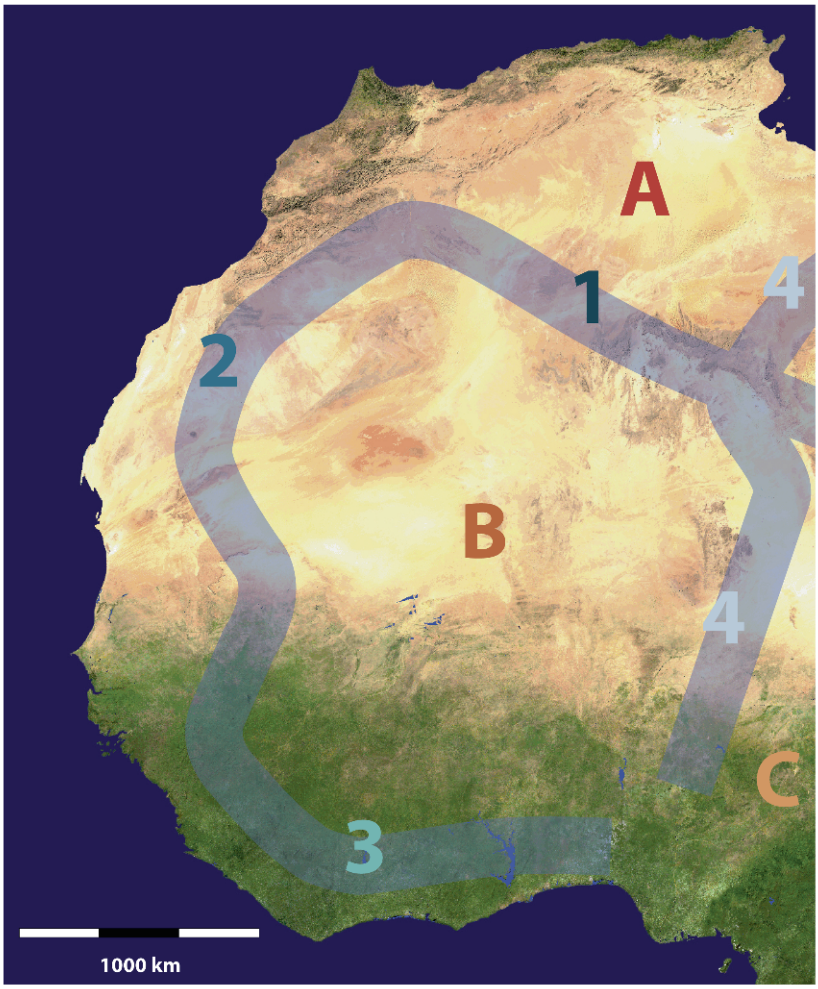
The African continent is unique in its nearly symmetric geographic situation at the earth's equator. This important environmental characteristic of the continent has produced a very broad latitudinal gradient of parallel tropical climate and vegetation zones and adjacent subtropical outlying areas. The coastal zone of West Africa is part of the inner humid tropics. Several different types of sub-humid tropical savanna are found north and south of the equator, in which the duration of the rainy season and the amount of total rainfall decline. The transition from the outer semi-arid and arid tropics to the arid and semi-arid subtropics occurs in the Sahara. With the exception of the Atlas Mountains, West and Northwest Africa are geographically similar to lower Africa, with an average elevation of 300 meters above sea level (Morgan and Pugh 1969, Lloeje 1972).

This exemplary zonal physiographic arrangement in Africa allows for a ready differentiation between relief regimes (see sect. I-3.1). The dominance of this 'horizontal' ecological arrangement can be considered the key geomorphic characteristic of Africa (Wiese 1997). Flat terrains of different genesis are the typical relief elements of the continent. These are expressed either as extensive peneplains or as alluvial plains in coastal areas and interior basins (e.g. West-Saharan Basin). Epeirogenetic processes, such as the uplift of large-scale threshold zones (e.g., Upper-Guinea Range) and the relative drift of extensive basins, have generated large scale landforms (see fig. I-3.2.1).

I-3.2.1 Geomorphological provinces of Benin

Benin includes three principal geomorphological provinces – the Coastal Alluvial Basin, the Upper-Guinea Range and the West-Saharan Basin. The spatial arrangement of these three provinces within Benin is closely linked to the main geological units present in the country's sedimentary basins. These are the Volta, Kandi and Coastal Basins in northern and southern Benin and the Dahomeyen series crystalline basement complex located in Central Benin (see fig. I-3.2.2).

The topographic relief in Benin is generally low, varying only a few meters from the coastal plain northwest to the Atacora mountain range, with the country's highest elevation point at Mt. Sokbaro (658 meters asl).



Geomorphological Provinces of West and Northwest Africa

Basins:
A - South-Algerian Basin
B - West-Saharian Basin
C - Tschad Basin

Ranges:
1 - Mid-Saharian Range
2 - West-Saharian Range
3 - Upper-Guinea Range
4 - Air Range

Cartography:
H.Hodam after
Wiese, B. (1997)
Data Source:
Landsat mosaic (NASA)
overlayed DTM (SRTM/DLR)

Fig. I-3.2.1: West and Northwest Africa natural regions, including major basins and ranges (Source: Wiese 1997).

As parts of the greater West-Saharan Basin, the Coastal and Kandi Basins are characterized by even landscapes with gentle, hilly plateaus. These are the result of varying resistance of the original sediments and deposits in the region to erosion. Additionally, the southern Coastal Basin includes a network of lagoons and estuaries. The Volta Basin is characterized by seasonally flooded plains between the Pendjari river and the Atacora range. The widespread basement complex of the Upper-Guinea range is framed by these sedimentary basins in Central Benin. This basement is divided NNE-SSW into western and eastern blocs by the Kandi fault. The land surface of the basement varies depending on the parent rocks. The surfaces may be slightly undulating, like the granitic-gneissic Parakou Plateau or Kourande-Pehonco peneplains. They may also be strongly fractured, like the granitic Pira peneplain, which transitions into the Lower Ouémé basin. Embedded in the basement complex are typical seasonally waterlogged linear depressions; such 'inland valleys' are widespread in sub-Saharan Africa. The most rejuvenated landscape of the basement is the Nikki peneplain with its characteristic scattered inselbergs.

I-3.2.2 Geomorphological provinces of Southern Morocco

Morocco is located at the northwestern edge of the African Continent and is characterized by pronounced topographical gradients. These gradients include several regions: the northern coastal plains around Rabat and Casablanca; the High Atlas Mountains; the Antiatlas Mountains (part of the West-Saharan Range); and the alluvial plains of the Saharan basin (see fig. I-3.2.3). The Drâa catchment shares three of these geomorphic provinces. It includes complex climatologic, hydrologic and vegetation regimes due to its high elevation range between Lake Iriki (421 meters asl) and M'Goun (4,071 meters asl).

The three geomorphic provinces of the Drâa catchment represent very different geological periods. The dominant crystalline bedrocks within the Antiatlas range are of Precambrian age. A mix of Mesozoic and Tertiary calcareous and silicate rocks are found in the High Atlas Mountains and in sediment-filled basins on the fringe of the Sahara Desert. Due to the extreme topographic and hydrological regimes, intensive agriculture in Morocco occurs almost exclusively in river oases like the Drâa valley. Principal urban settlements like Ouarzazate and Zagora are located along the perennial rivers.

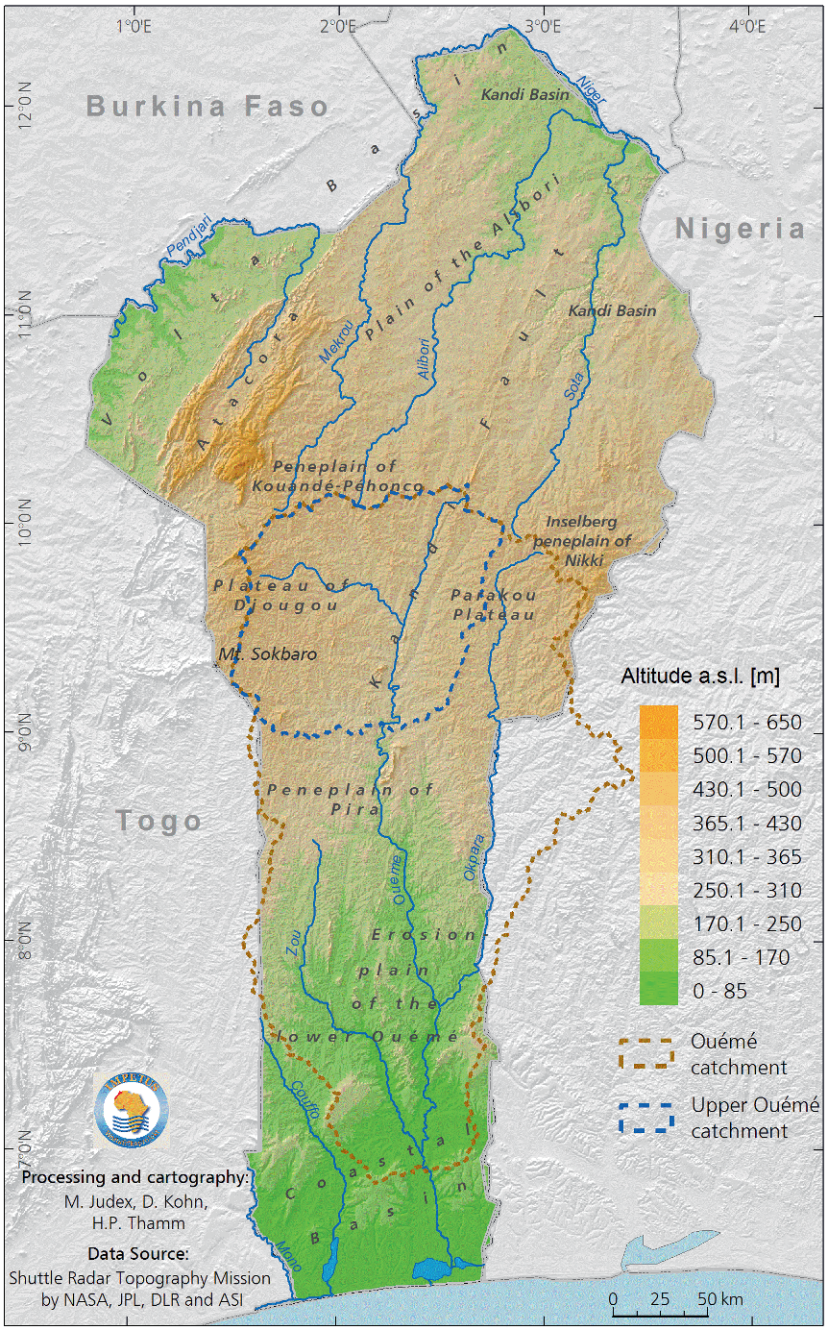


Fig. I-3.2.2: Topography of Benin, including major geomorphological provinces (Source: Modified after Giertz and Schönbrodt 2008).

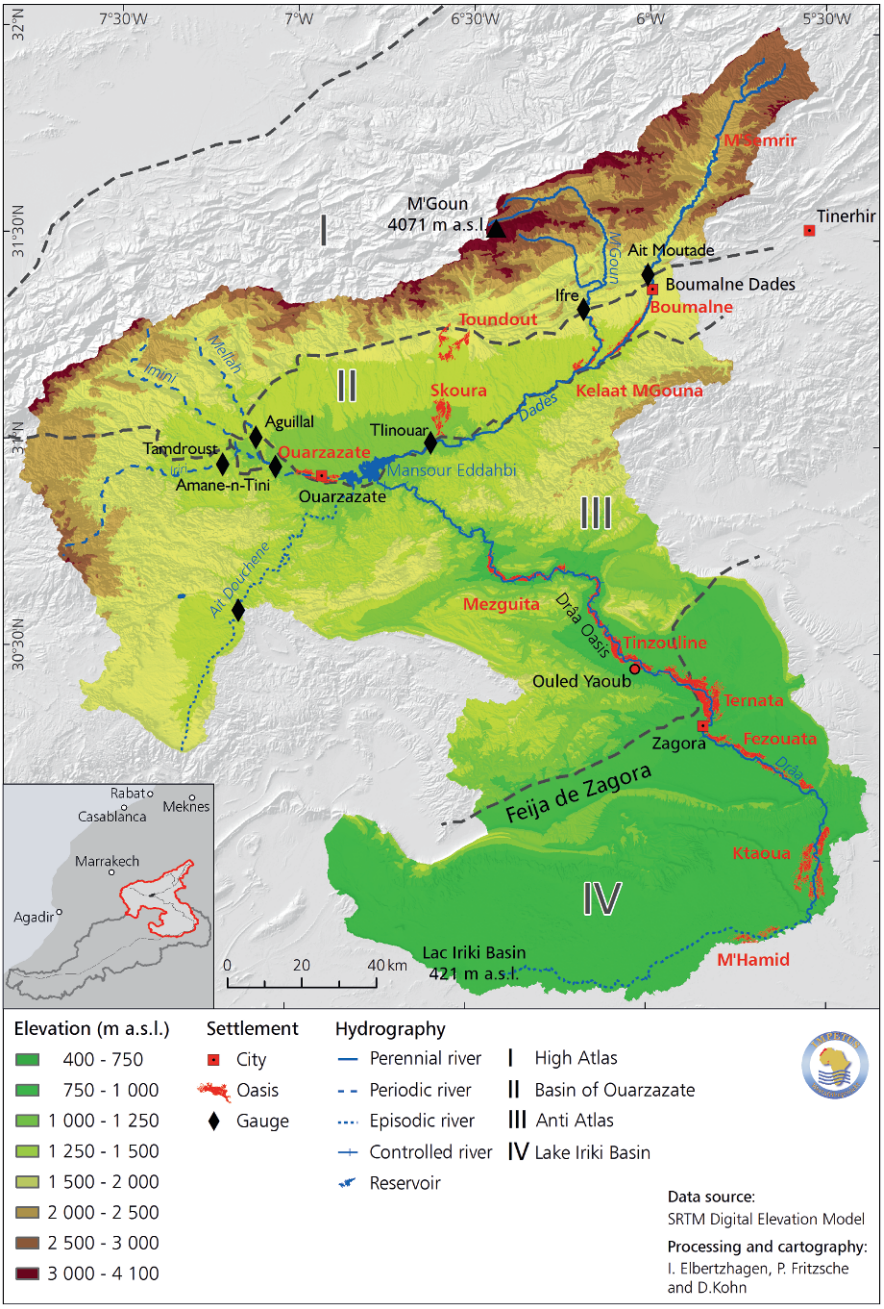


Fig. I-3.2.3: Topographic map of the Drâa catchment in Southern Morocco, including the major geomorphological provinces (Source: Elbertzhagen and Fritzsche 2008).

I-3.3 Soils

T. Gaiser, H. Goldbach, S. Giertz, C. Hiepe, and A. Klose

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Soil genesis and distribution depend on the driving forces of climate, geology, topography, biotic interactions and time. The soils in the western and northern parts of Africa have developed under a predominantly subtropical to tropical climate with a relatively high mean temperature, but variable humidity (see sect. I-3.1). A steep humidity gradient exists from the central Sahara to the Atlas Mountains and to the Mediterranean in the north. This humidity gradient is even more pronounced from the Sahara Desert south toward the Atlantic Ocean. In general, the soils of deserts and semi-deserts are much younger than the soils of humid tropics. In the semi-arid sub-tropical climate zones are soils that have developed since the last glacial period (20,000-30,000 years). Although there was no glaciation, evapotranspiration was lower and annual precipitation was probably twice as high as today, indicating a kind of sub-humid period. Older soils in these regions date back to the Tertiary, but most soils have developed within the last five million years. In the semi-arid and sub-humid tropical zones, Climatic Changes in the last two million years with humid phases and higher precipitation are the reason for the occurrence of relictic soil formations. Typically, the translocation of soil material (erosion by water in humid periods and erosion by wind predominantly in the dryer period) has occurred during these phases, removing soils partly or entirely. Thus, parent material was exposed to the surface and soil formation started again. In the humid zones, the land surface was more stable. Depending on parent materials and topographic position, typical soils from arid regions, such as Calcisols, Regosols, Arenosols and Leptosols, cover the hyper-arid and arid parts of the Sahara (see fig. I-3.3.1), usually having a yermic phase (soil surface that usually consists of surface accumulations of rock fragments embedded in a loamy vesicular layer) (WRB 1998; FAO/AGL 2003). In the semi-arid northern fringes toward the Mediterranean, neutral to slightly acid Calcisols, Cambisols and Luvisols are the dominant soil groups. In the semi-arid southern fringe, acidic to highly acidic Arensols developed from sand dunes or sand cover predominate. These differences between the northern and southern Saharan fringes are due to the contrasting parent materials and paleo-climatic conditions. At the northern fringe, limestone and loess-like materials determine the formation of calcareous soils, where rooting may be restricted by indurated layers. In contrast, the soils derived from the Aeolian sands and sand covers south of the Sahara are free of carbonates. Hence, chemically poor, acidic soils have developed that are deeply rootable but have a low water retention capacity.

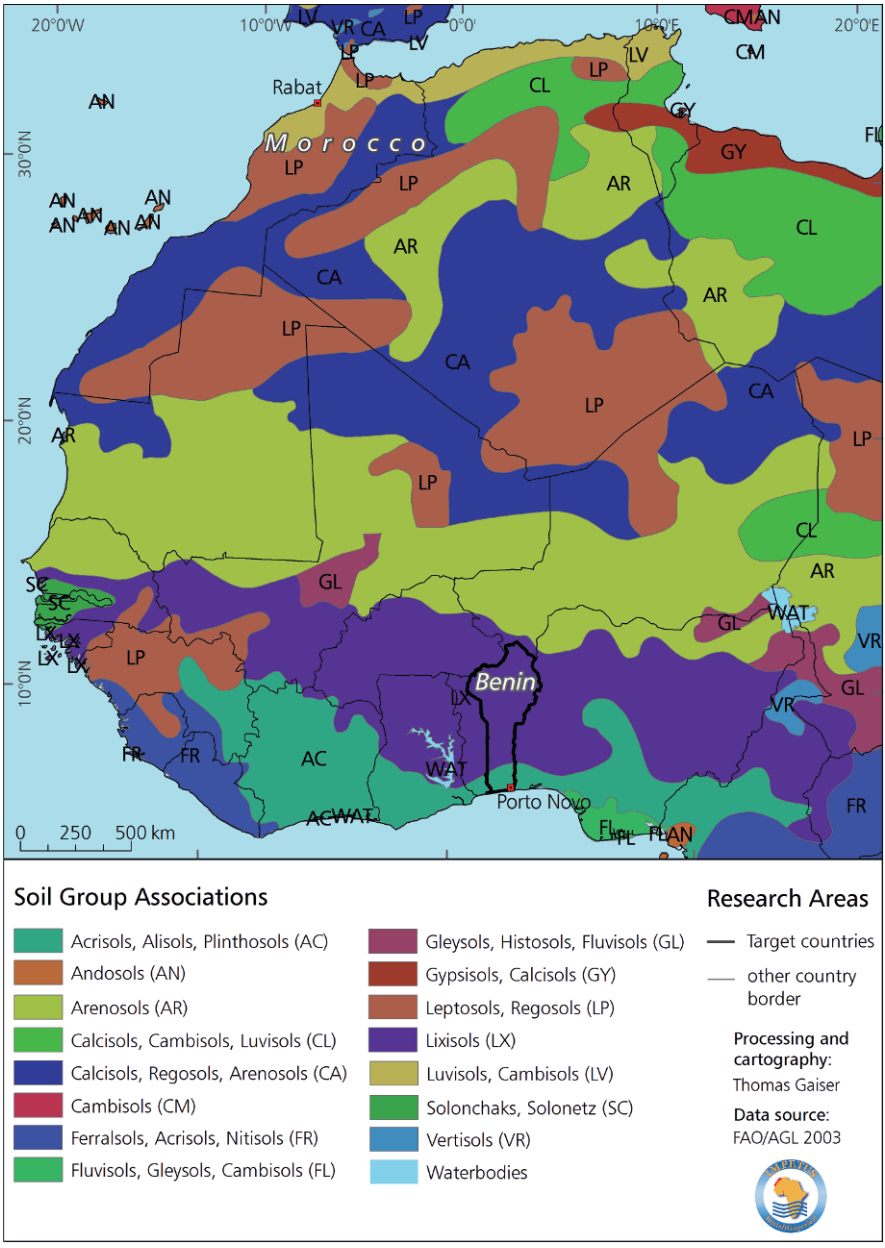

Fig. I-3.3.1: Soil associations with dominant soil groups across Northwestern and Western Africa (Source: According to FAO/AGL 2003).

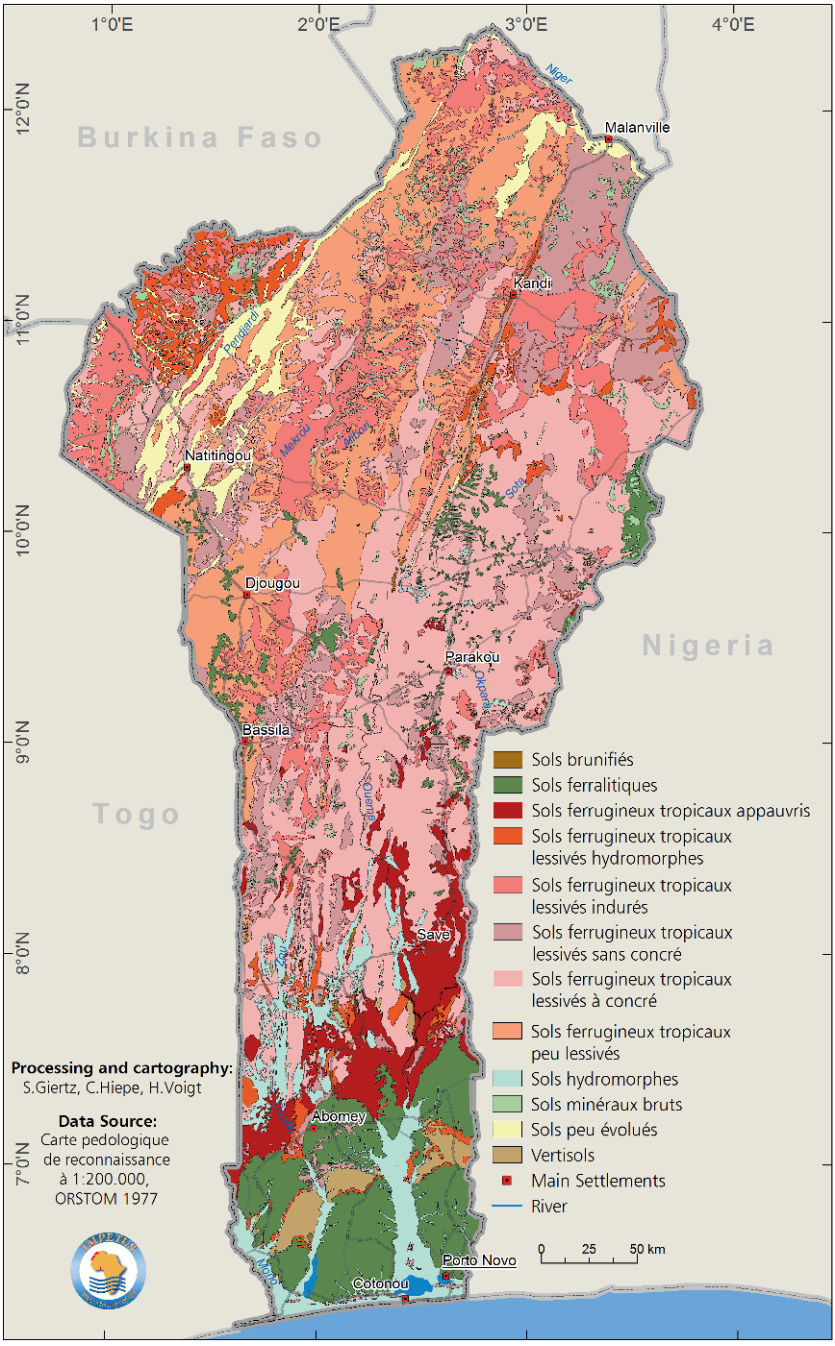

Fig. I-3.3.2: Soil distribution in the Republic of Benin (Source: Judex and Thamm 2008).

Slightly acidic soils with sandy to loamy topsoils and increasing clay content in the subsoil (Lixisols, Luvisols) occur in the sub-humid savanna zone around 10°N. Toward the more humid areas on the coastal belt, highly weathered Acrisols or Ferralsols with low base saturation become increasingly important.

I-3.3.1 Soils of Benin

Figure I-3.3.2 gives an overview of the soil distribution in Benin. The regional differentiation of soils in Benin roughly corresponds to the large geomorphological units. On the crystalline basement, which is predominant in the northern and central part of Benin, mainly fersialitic soils (*sol ferrugineux tropicaux*) occur. Most of the fersialitic soils in central Benin are characterized by clay translocation and iron segregation (*sols ferrugiuex tropicaux lessivé à concretion*), which lead to a clear horizon differentiation (Faure and Volkhoff 1998). These soils can be classified as Lixisols according to the WRB. In the Atacora mountain range are mainly shallow Leptosols and poorly developed Regosols (*sols peu evolués*). In the wetter southern part of the Benin basin, ferrallitic soils (*sols ferrallitques*) are predominant. They are highly weathered, sesquioxide rich, and mainly kaolinitic and are characterized by small textural changes within the soil profile. Vertisols, which are characterized by high clay content, can be found on the Lama depression in the southern sedimentary basin. Furthermore, Cambisols (*sols brunifiés*) occur on basic rocks and are distributed over the whole country. Large areas with hydromorphic soils (Fluvisols) can be found on the alluvial plains of the Mono and Ouémé rivers in the south of Benin.

The described soil distribution on a regional scale does not reflect the high small-scale variability of soils that can be found in Benin. Junge (2004) investigated soils at the local scale in the Aguima catchment (30 km²). She describes a typical catena with Lixisols/Acrisols on the upper and middle slopes. These are followed by Plinthosols on the downslope, gleysols in the inland valleys and fluvisols on the fluvial plain.

In addition to the French soil maps, a SOTER-map was created by Igué (2000) for South and Central Benin according to the SOTER concept (SOil and TERrain; van Engelen 1993). To separate the SOTER mapping units, Igué (2000) used basic maps of geology, soils and topography. It is planned to complete the SOTER map for the whole of Benin.

I-3.3.2 Soils in the Drâa valley of Southern Morocco

Soil surveys in the Drâa basin are very rare. Recently, 211 soil profiles have been described and analyzed. Figure I-3.3.3 reflects the distribution of the major soil types. Other soil surveys concentrate on the agriculturally used oases. In these date palm oases, the following soils are identified: *sols peu evolués d'apport fluviatil* (Fluvisols), *sols peu evolués d'apport d'irrigation* (irragric Anthrosols), *sols peu evolués jeunes sableux* (Arensols), *sols peu evolués jeunes bruns* (Cambisols), *sols mineraux bruts d'apport fluviatil* (Fluvisols), *sols mineraux bruts d'apport d'irrigation* (irragric Anthrosols), *sols mineraux bruts d'apport éolien* (Arenosols) and *sols isohumiques bruns subtropicaux* (calcic Kastanozems) (Brancic 1968; Radanovic 1968a, 1968b, 1968c). In the brackets, the supposable WRB soil types are given. The soils are formed on loamy, loess-like flood deposits. The texture of the oasis soils is mainly sandy loam (SL) or sandy clay loam (SCL) (see fig. I-3.3.4). They partially suffer from salinization, which increases from the northernmost oases toward the south, and they show a lower organic matter content (Bouidida 1990).

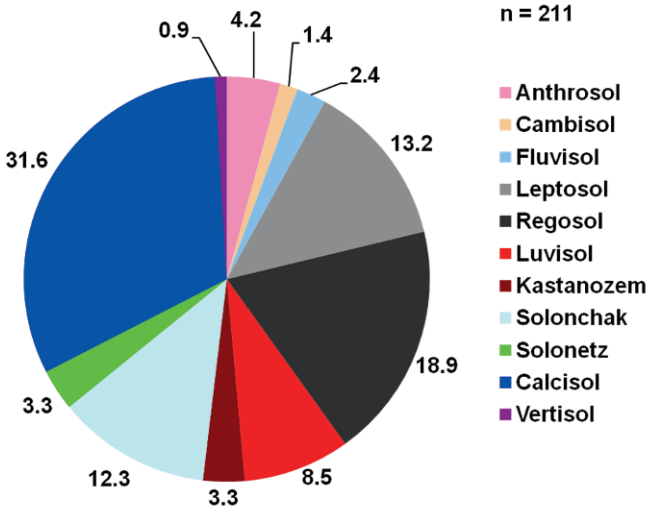

Fig. I-3.3.3: Identified soil types in the Drâa catchment and their frequency [%].

The only soil map of the area is given by Cavallar (1950) at a scale of 1:500,000. In the High Atlas Mountains, this map delineates soils typical for sub-humid (Luvisol) and steppic (Kastanozem and Chernozem) climates. This indicates the relatively humid conditions in the High Atlas. Furthermore, Calcisols are found in the zones where Jurassic limestone is outcropping. Leptosols are soils typical for mountainous areas with steep slopes, as soil profiles are shallow and disturbed by erosion. In the sedimentary basins (Ouarzazate and Tazenakht basins), Kastano-

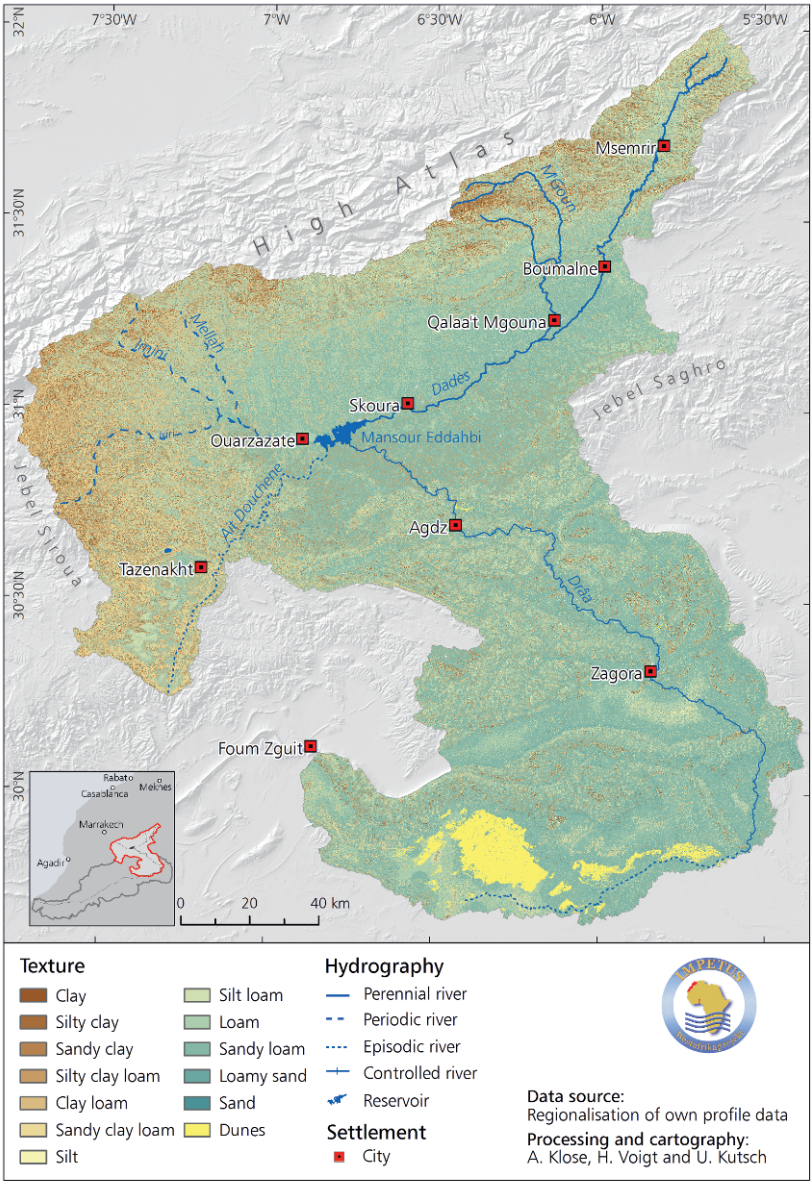

Fig. I-3.3.4: Topsoil texture in the Drâa catchment extrapolated from own soil profile data (Source: Schulz and Judex 2008).

zems, Chernozems and Regosols are mapped. The occurance of Kastanozems and Chernozems is surprising for this area, as their development demands a steppe climate and relatively dense vegetation cover to form topsoils rich in organic matter. The climatic conditions, which favor steppe soils, are presently not given in the Sedimentary Basins. However, Regosols can be expected in the area. In the Antiatlas Mountains, Leptosols are listed as typical mountainous soils. The genesis of Cambisols and Luvisols requires chemical weathering and translocation processes, and thus the presence of water. They can develop only under relatively humid conditions, or they can be conserved as paleosols. The latter is possible in the Antiatlas Mountains as tectonic activity is low in the area, which means the landscape has been relatively stable since the Carboniferous age. Calcisols are also denoted in the Antiatlas Mountains. This is astonishing, as the mostly crystalline parent material is nearly free of carbonate. The development of Calcisols has to be ascribed to the input of aeolian dust comprising carbonate. Typical desert soils are mapped in the Saharan Foreland, reflecting the arid conditions. The oases are dominated by Fluvisols and Regosols, as can be concluded from their location adjacent to the riverbeds.

I-3.4 Climate

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West and Northwest Africa are located in two major climate zones: the subtropical climate north of the Sahara and the tropical climate south of the Sahara. These major zones can be sub-divided into smaller climate units depending on their hygric and thermal characteristics. The following subsection will provide a short overview of the climates of Northwest and West Africa and of recent trends in precipitation and temperature.

I-3.4.1 Subtropical climate of Northwest Africa

The subtropical climates of the Maghreb range from moderate, influenced by maritime Atlantic and Mediterranean weather systems, over cool, semi-arid to subhumid mountain climates in the Atlas Mountains, to hot and dry, steppe and desert climates at the northern boundary of the Sahara. In terms of the annual cycle of rainfall and temperature, the Atlantic and Mediterranean regions are characterized by moderate, wet winters and hot, dry summers (Griffiths 1972; Griffiths and Soliman 1972). Due to the lack of observations, information about seasonal snow coverage in the mountains of northwest Africa is vague and often limited to non-instrumental observations. During the winter, a multi-day snow cover in the Rif and Middle Atlas Mountains frequently occurs at altitudes above 1,500 m, whereas the High Atlas Mountains usually experience snow cover only at altitudes higher than 2,000 m (Mensching 1957). A persistent snow cover in winter is limited here to altitudes above 3,000 m. However, instrumental observations (Schulz 2008) show that at the summit level of the High Atlas Mountains, i.e. at an altitude of about 4,000 m, snow covers the ground for more than five months. By contrast, on its southern slopes between 2,000 m and 3,000 m, snow cover persists between one or two days and rarely up to weeks after a snowfall event. The arid regions south of the Atlas Mountains are marked by weak seasonal variations with episodic rainfall. Here, winters are mild and summers are extremely hot with temperatures exceeding 45°C in places.

The atmospheric input to the terrestrial water budget is determined by the rainfall and evapotranspiration amounts. Both quantities are difficult to measure, and

observation networks are sparse. As can be seen in figure I-3.4.1a, mean annual precipitation in the Rif Mountains in northwest Morocco exceeds 1,000 mm and reaches up to 800 mm in the High Atlas Mountains (see fig. I-4.3.3 in sect. I-4.3). In the Antiatlas Mountains, annual precipitation still amounts to about 500 mm in the long-term mean. Some salient dry zones are the Marrakech Basin, the Souss Valley, the Ouarzazate Basin, and the high plateau areas of northeastern Morocco. Potential evaporation is extremely high in all areas at well-above 2,000 mm per year (Griffiths and Soliman 1972).

Knippertz et al. (2003) found three homogeneous rainfall regions with respect to annual precipitation variability (see small maps in fig. I-3.4.2a). These are the northern and western parts of Morocco, the 'Atlantic region' (ATL), northeastern Morocco and northwestern Algeria close to the Mediterranean coast, the 'Mediterranean region' (MED), and the Moroccan and Algerian stations south of the Atlas

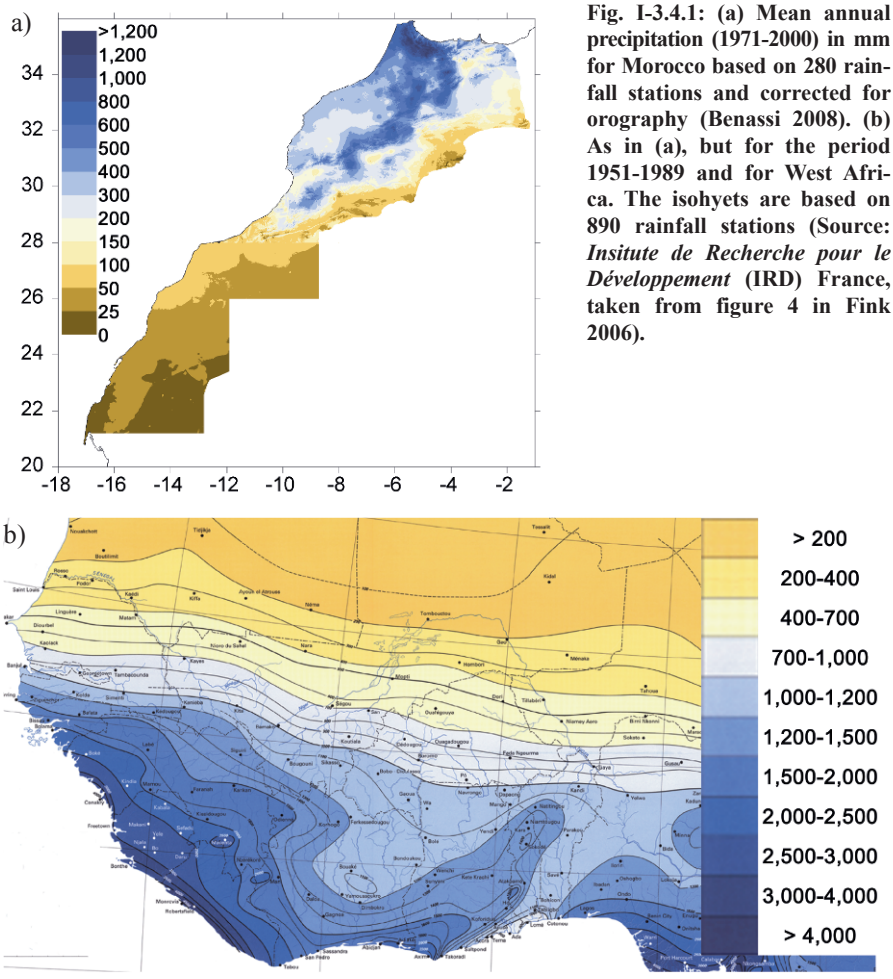

Fig. I-3.4.1: (a) Mean annual precipitation (1971-2000) in mm for Morocco based on 280 rainfall stations and corrected for orography (Benassi 2008). (b) As in (a), but for the period 1951-1989 and for West Africa. The isohyets are based on 890 rainfall stations (Source: *Insitute de Recherche pour le Développement* (IRD) France, taken from figure 4 in Fink 2006).

Mountains called the 'South of the Atlas region' (SOA). In order to visualize climatic rainfall variability, time series of the Standardized Precipitation Index (SPI) after McKee et al. (1993) for the hydrological year (September–August) are shown in figure I-3.4.2a. The time series reveal considerable interannual and decadal variability. In the MED region, below average rainfall has prevailed since the late 1970s (Fink et al. 2008a), whereas in the ATL region precipitation is low from the late 1970s to the early 1990s, but with some wet years during the late 1990s and after 2000 (see fig. I-3.4.2a). Note that both regions exhibited rather wet 1960s after which the afore-mentioned strong drying trend set in. In the SOA region, precipitation has most recently been above average around the 1990s and remained close to the long-term average since then (see fig. I-3.4.2a). A significant warming trend in the annual averaged temperature in the Maghreb has been detected since the middle of the 20th century. As a consequence, a general tendency toward drier and warmer climates in all regions of the Maghreb has been found (Fraedrich et al. 2001; Born et al. 2008a). This in particular has led to an upward movement of the snow-line in the high mountain areas.

I-3.4.2 Tropical climate of West Africa

The majority of sub-Saharan West Africa is situated in a wet and dry tropical climate. Depending on the latitude and the distance from the Atlantic Ocean, the degree of aridity increases from south to north and to a lesser extent from west to east. The Sahel zone, which is the region north of about 12.5°N, possesses a semi-arid climate. The Soudanian zone, between about 9 and 12.5°N, is sub-humid whereas parts of the Guinea Coast are humid. Annual mean temperatures have a range of 26–30°C in all three regions. A clear distinction in the aforementioned climate zones relates to the overnight temperatures and near-surface humidity in winter. In the Sahel, night-time temperatures regularly fall below 10°C, and the relative humidity stays below 50% throughout the day. At the Guinea coast, minimum temperatures at night lower than 18°C are rarely observed, and the high relative humidity makes the weather muggy throughout most of the year.

The seasonal rainfall distribution is determined by the annual march of the rainy zone (see section I-5.1), which starts to move slowly on the continent in March and swiftly retreats back to the tropical Atlantic Ocean between September and November. As a consequence, the Sahel and most parts of the Soudanian zone have a unimodal rainfall season that peaks in August whereas the Guinea coast exhibits a bimodal rainfall season with peaks in June and October. The second rainy season along the coast is less pronounced. The seasonal migration of the rainy zone in and out of the sub-continent also determines the length of the rainy season and, thereby, the total annual rainfall amount.

The following salient features describe the rainfall distribution in West Africa for the period 1951–1989 (see fig. I-3.4.1b). First is the strong rainfall decrease

from the northern Soudanian zone to the Sahara. The mean annual rainfall declines from 1,000 mm to 200 mm over a distance of about 550 km. Thus, the rainfall decreases northward by about 145 mm per 100 km, resulting in a strong natural vegetation gradient. Second, particular wet regions occur where the moisture-laden monsoonal southwesterlies blow perpendicular to the coastline or are lifted due to coastal orography. This happens at the southwest coast with the adjacent Guinea Mountains, the west of the Cape of The Three Points, the mouth of the Niger River, and the Cameroon Mountains. Finally, a dry zone stretches from the Gold Coast across southern Togo and Central Benin into northwestern Nigeria. This region is called the Ghana-Dahomey dry zone (Vollmert et al. 2004). Data on evaporation are rare. Daily WMO (World Meteorological Organisation) Class A pan evaporation data for 2006 at six Beninese stations indicate a typical potential evaporation of 10–12 mm day^{-1} during the peak of the dry season in northern Benin. This drops to 2–4 mm day^{-1} at all stations during the rainy season.

The two Sahelian regions (see fig. I-3.4.2b) experienced a multi-decadal wet episode between 1930 and the mid-1960s. This was only temporarily interrupted by a few anomalously dry years in the 1940s, causing a secondary minimum of the 11-year running mean. A multi-decadal dry episode commenced around 1970 with notable drought periods in the early 1970s and early to mid-1980s. In the west and central Sahelian zones, the last 18 years since 1990 are characterized by a return to near-normal rainfall conditions, as indicated by the 11-year running mean curves that approach or, in the case of the Central Sahel, even cross the zero

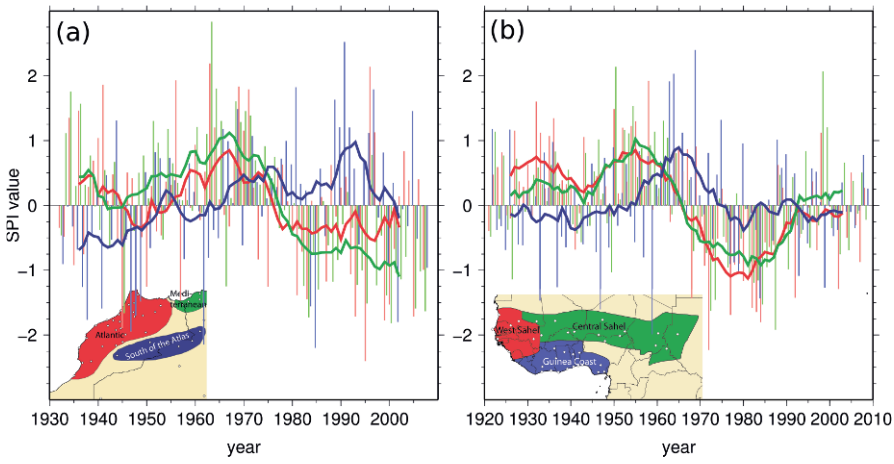

Fig. I-3.4.2: (a) Time series of the Standardized Precipitation Index (SPI) for September – August 1930/31 – 2007/08 for the ATL, MED, and SOA regions (for more details, see text). The 11-year running means are shown as solid curves. (b) As in (a), but based on precipitation anomalies for June–September 1921–2008 for the Western Sahel, the Central Sahel, and the Guinea Coast. The small maps display the homogeneous rainfall regions. For details regarding these regions and the computation of the Maghrebian and West African time series, see Knippertz et al. 2003, Born et al. 2008b, and Fink et al. 2008b and references therein.

line in figure I 3.4.2b. Lebel and Ali (2009) also recently noted a rainfall recovery in the Sahel, although they found an unabated dryness in the western Sahel. Even though year-to-year rainfall variability is higher in the more densely-populated coastal areas, it is evident that sequences of dry years dominated the first half of the past century and have prevailed since the 1970s (see fig. I 3.4.2b). The only prominent wet decade at the Guinea coast was the 1960s, during which four of the five wettest years on record occurred. For a discussion of the long-term rainfall and temperature trends in Benin, the reader is referred to section I-5.1.

I-3.5 Hydrology

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Hydrological processes differ significantly between the north and south of the Sahara. In Northwest Africa, only a few permanent or intermittent flowing rivers can be found. With decreasing precipitation, sporadic discharges occur in wadis that are characterized by a river bed consisting of course material with a high infiltration rate, causing significant water losses. Only rivers originating in mountainous areas flow permanently, but they often end in a terminal lake like the Dades-Drâa river system in Morocco, which drains into Lake Iriki.

Table I-3.5.1: Water availability per capita and year for selected countries in West and Northwest Africa (Source: FAO AQUASTAT 2009).

Country	Water availability m³/capita/a	Rainfall [mm/a]	Population	Dam capacity [km³]
Algeria	443	89	33,351,000	6.00
Benin	3,585	1,039	8,067,000	0.04
Burkina Faso	933	758	14,358,000	5.10
Cote d'Ivoire	4,794	1,348	18,914,000	38.10
Ghana	2,489	1,187	23,008,000	148.00
Mali	7,458	282	11,968,000	13.60
Mauritania	3,826	92	3,044,000	0.89
Morocco	934	346	30,853,000	16.10
Niger	2,710	151	13,737,000	0.10
Nigeria	2,252	1,150	144,720,000	44.20
Senegal	3,811	686	12,072,000	1.60
Togo	2,930	1,168	6,410,000	1.71
Tunisia	459	207	10,215,000	2.56

The most important rivers in West Africa are the Niger, the Senegal and the Volta, which are characterized by a permanent discharge (see fig. I-3.5.1). Smaller rivers, like the Ouémé river in Benin, flow periodically, following the time course of the precipitation. According to Korzun (cited in Shanin 2002), the runoff coefficient (the percentage of precipitation that appears as discharge) varies between less than

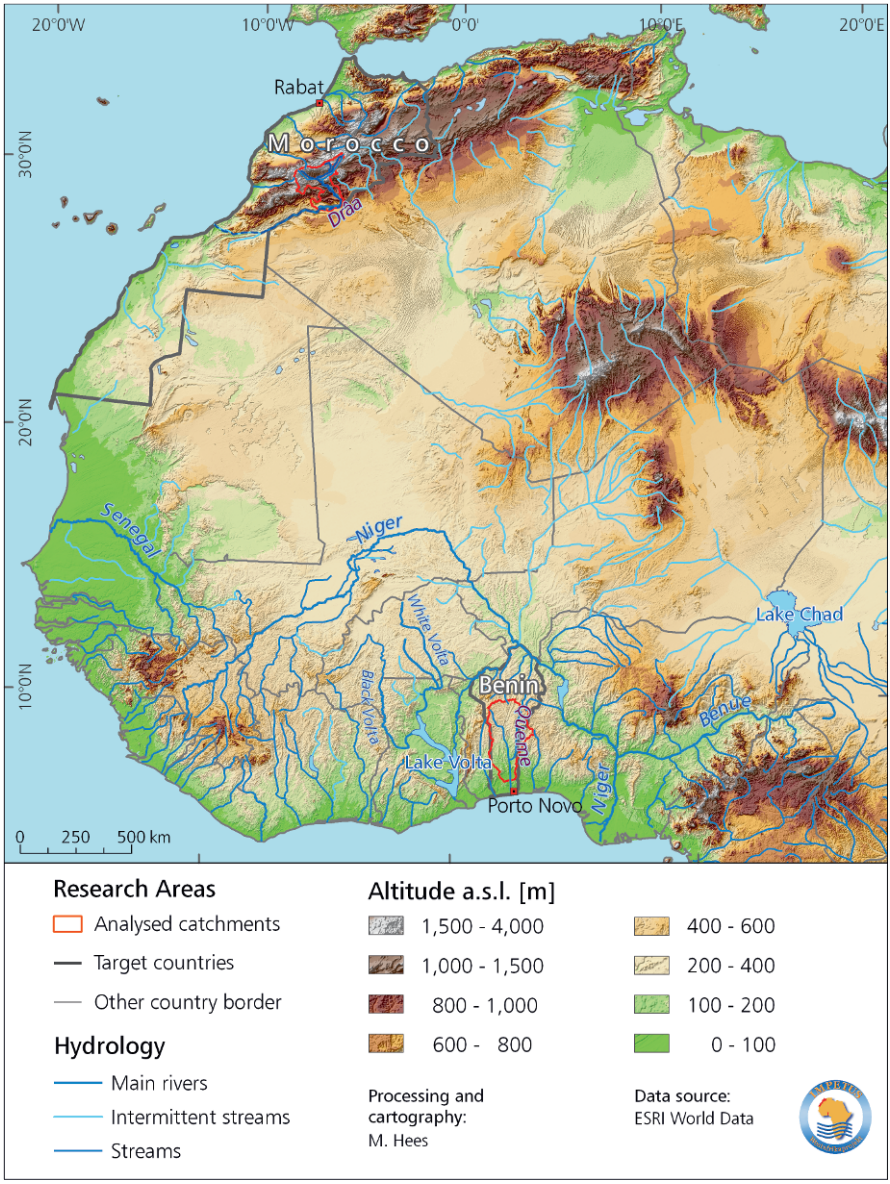

Fig. I-3.5.1: Important river systems and reservoirs in West and Northwest Africa.

5% for Northwest Africa up to 10-30% for West Africa. Mountainous areas, especially in western Africa, can show runoff coefficients of more than 50% due to high rainfall amounts.

Water availability per capita and per year also varies significantly between different countries (Benin: 3,585 m^3 per capita and year; Morocco: 934 m^3 per capita and year; see table I-3.5.1), and it depends on precipitation as well as population density. A large variability exists concerning the dam capacity, which ranges between 0.04 km^3 (Benin in 2001) and 148 km^3 (Ghana in 2003) (FAO AQUASTAT 2009).

I-3.5.1 Ouémé basin

The network of major rivers in Benin is given in figure I-3.2.2. Benin belongs to the river systems of the Niger, the Volta, the Mono, the Couffou, and the Ouémé. The length of the Ouémé river is about 510 km, and the two most important tributaries, Zou and Okpara, have a length of 150 and 200 km respectively. The Ouémé river drains into Lake Nokoué (150 km^2) and flows through the coastal lagoon system into the sea. Important wetlands are found in the south of Benin (e.g., Lake Nokoué, Lake Ahémé, Lake Toho, and the coastal lagoons), in Pendjari national park and in the floodplains of the Niger River. Inland valleys (in French, *bas fonds*) that are regularly flooded during the rainy season are widespread. A study by Giertz et al. (2008) revealed the importance of inland valleys for food production.

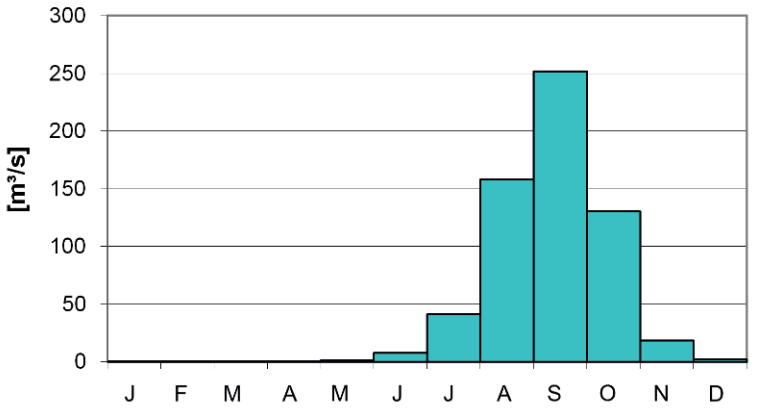

Fig. I-3.5.2: Measured discharge at the Bonou gauging station (49,285 km^2) of the Ouémé River, Benin (Source: *Direction Générale de l'Eau Benin*).

As an example, the measured discharge at the Bonou gauging station (49,285 km^2) at the Ouémé river, Benin, is given in figure I-3.5.2. The temporal dynamic of the hydrograph follows the rainy season, with a six to eight-week delay in runoff onset.

As rainfall variability is high in the Ouémé basin, the annual discharge shows the same trend. Rainfall and runoff are characterized by below-mean values for the last 30 years (see fig. I-3.5.3). The runoff coefficients vary from 0.10 to 0.26 of the total annual rainfall and are lowest for the savannah and forest landscapes. For all studied sub-catchments, the highest runoff coefficients were obtained in the years with the highest annual rainfall. Irrigation, in fact, plays a minor role in Benin's agriculture. According to the FAO (2005), only 12,258 ha were equipped for irrigation in 2002.

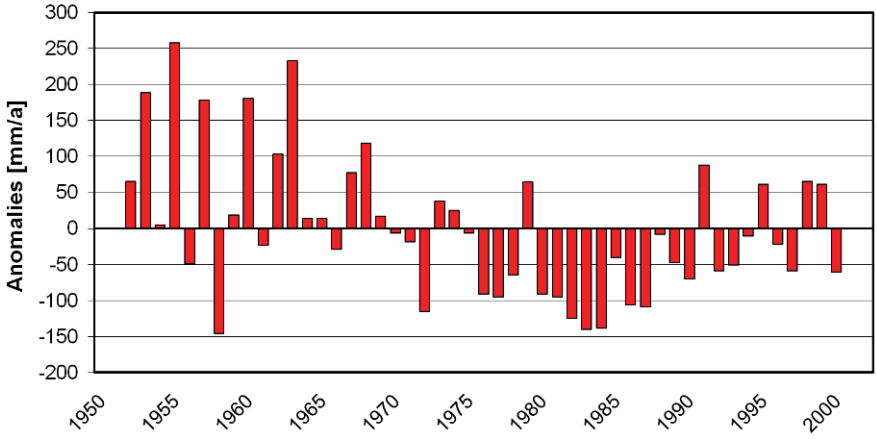

Fig. I-3.5.3: Deviation of the annual discharge of the Ouémé at the Beterou station (10,083 km²) from the mean value for the period 1950 to 2000 (Source: *Direction Générale de l'Eau Benin*).

I-3.5.2 Drâa basin

The river network of the investigated catchment south of the High Atlas Mountains is given in figure I-3.2.3. Only the Dades river flows permanently because of its origins in the High Atlas Mountains, which are characterized by higher precipitation amounts (rain and snow) and by karstic aquifers. Before the Mansour-Eddahbi reservoir near Ouarzazate was built in 1972, runoff frequently reached Lake Iriki during floods. This is the Drâa's endorheic lake, as the amount of water is not sufficient to overcome the last 750 km to the Atlantic Ocean (Lower Drâa valley). The reservoir was constructed to assure irrigation, generate hydroelectric energy, and reduce flood risk. The mean runoff coefficient of the upper reservoir basin ranges between 5 and 20%. However, the region in which a significant amount of discharge is generated is the region above 1,900 m as it covers one third of the area in which half of the precipitation falls. All other rivers in this re-

gion are only episodically water-bearing. Their contribution to the total discharge is low and difficult to quantify due to missing gauging stations. Water stored in the reservoir is used for water supply of Ouarzazate and other cities, but losses due to evaporation are significantly higher than urban water requirements (about 5 vs. up to 50 Mm³/a). Outlets from the Mansour Eddahbi reservoir represent the major water input of the middle Drâa valley. However, they depend on the filling level, and they show strong interannual variability (see fig. I-3.5.4.). The goal of having an annual outlet of 250 Mm³ has only been reached in 43% of the years. According to the FAO (2005), irrigation agriculture is widespread in Morocco with a total of 1.484 Mha in 2004. In the Drâa valley, 1.7% of the landscape is under irrigation, which totals about 50,000 ha.

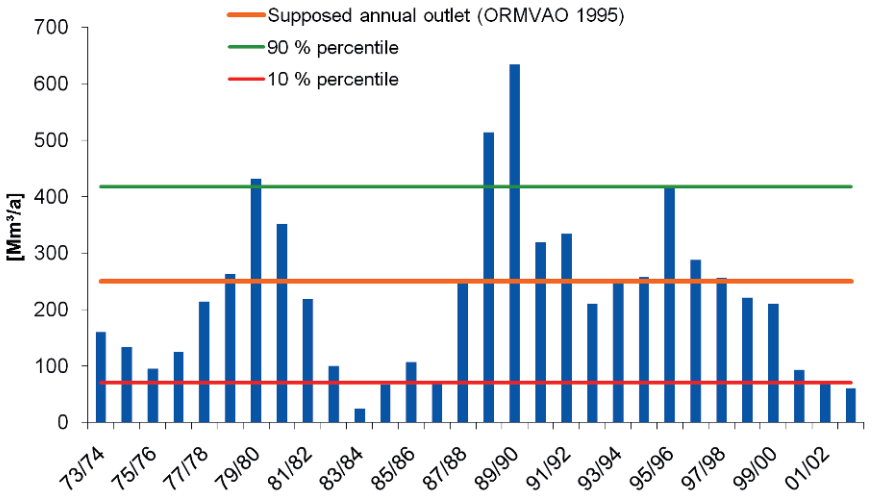

Fig. I-3.5.4: Water release of the Mansour-Eddahbi Reservoir. A mean annual discharge of 250 Mm³/a is required to guarantee irrigation agriculture downstream (Source: *Office Régionale de Mise en Valeur Agricole de Ouarzazate*, Morocco).

I-3.6 Flora and vegetation

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Most of tropical West Africa is divided between two phytochoria (White 1983). The costal lowland rain forest is part of the Guineo-Congolian regional center of endemism (comprising approx. 8,000 spp., 80% endemic) whereas drier forest types and savannas belong to the Sudanian regional center of endemism (approx. 3,750 spp., 33% endemic). Today, agriculture (in particular, cash crop plantations) and other human activities have led to large-scale deforestation and fragmentation, leaving only small relict blocks of natural vegetation types within a matrix of degraded secondary habitats.

The flora and vegetation of Northwest Africa is highly complex due to the fact that it forms a transition between the Holarctic and Palaeotropic floristic kingdoms. Northwest Africa comprises the Mediterranean Region, which is a center of plant endemism that has three regional transition zones (i.e., Mediterranean/Sahara, Sahara and Sahel). Most of the Mediterranean Region was formerly covered by various forest types with non-forest vegetation being confined to areas such as the coastal habitats and the higher mountains.

The transition zone in Morocco between the Mediterranean Region and the Sahara extends from the main ridge of the High Atlas to the southern chains of the sedimentary Antiatlas. Over a distance of less than 200 km, the vegetation changes gradually from Oromediterranean cushion shrubs and *Juniperus*-dominated woodlands over semiarid steppes with *Artemisia* and *Stipa* species to Saharan deserts. Within Morocco, we find about 4,500 vascular plant species, of which about 20% are endemic (Fennane 2004). Continuously increasing silvopastoral land use pressures and inappropriate forest policies over the last century have caused degradation and deforestation of woodlands and desertification of semiarid rangelands (Sarukhán and Whyte 2005).

I-3.6.1 Upper Guinean rain forest

The evergreen to semi-evergreen rain forests of West Africa are one of the world's hotspots of biodiversity (Myers et al. 2000). The rain forests extend from southern Senegal in the west to Ghana in the east. The Dahomey Gap in Ghana, Togo and Benin separates them from the Central African rain forests. Upper Guinean forests contain 2,800 vascular plant species (approx. 23% endemic). Families with nu-

merous endemics are, e.g., *Acanthaceae*, *Anacardiaceae*, *Leguminosae* and *Rubiaceae* (Jongkind 2004). Variation in floristic composition and structure is mostly gradual. It is, however, possible to classify different forest types (e.g., Guillaumet and Adjanohoun 1971). Current patterns of floristic composition and species richness in West Africa are the result of large-scale climatic disturbances in the past. During the dry and cool glacial periods of the Quaternary, rain forests contracted to small refugia (Maley 2001). Upper Guinean rain forests are disappearing rapidly under human pressure, and today, large, undisturbed forest patches have become increasingly rare. In many regions, only small island-like patches of forest remain that are surrounded by secondary grassland and plantations.

I-3.6.2 Woodlands and savannas

Following the climatic gradient from the Gulf of Guinea to the north, the lowland evergreen rain forests give way to dry forests, woodlands and savannas, which also dominate in the coastal areas of the Dahomey Gap. Most of West Africa was originally covered by different types of dry forests. Due to man-made fires, they have been converted to savannas that form near-natural ecosystems. Often, only fire-resistant tree species (e.g., *Parkia biglobosa, Vitellaria paradoxa*) that are of economic interest have been left over. There is, however, evidence that forests and savannas already co-existed with varying proportions long before human impact became stronger (Salzmann 2000). West African woodlands and savannas comprise about 1,500 species with *Combretaceae*, *Leguminosae*, *Poaceae* and *Rubiaceae* being important. With regard to plant species richness, the narrow transition zone between rain forest and savanna is outstanding. This zone is characterized by a mosaic of forest islands, gallery forests and savannas. Remarkably, the patchy landscape structure of this zone has been fairly stable, even under conditions of Climate Change over the last decades (Goetze et al. 2006). In general, the vegetation cover in woodlands and savannas is strongly influenced by edaphic conditions.

I-3.6.3 Azonal vegetation types

Among the azonal vegetation types, rocky outcrops and gallery forests occur throughout West Africa. The most important rock outcrops are granitic or gneissic inselbergs and laterite plateaus (Porembski 2000), which promote highly seasonal ecosystems. During the dry season, their appearance is rather dry and barren. In contrast, the rainy season reveals a multitude of habitat types and plant communities. Prominent among them are desiccation-tolerant vascular plants (e.g., *Afrotrilepis pilosa*) and carnivorous plants (mainly *Utricularia* spp.). Over the last few decades, human influences have caused severe degradation of these inselbergs and laterite plateaus.

Among the most detrimental of these impacts are fire, grazing and quarrying.

Gallery forests are located on river floodplains, where they are influenced by elevated water tables or periodic flooding. West African gallery forests are fairly homogenous in their floristic composition (Natta and Porembski 2003).

Most species-rich families in West African gallery forests are *Leguminosae*, *Euphorbiaceae* and *Rubiaceae*. Important are evergreen trees such as *Cynometra megalophylla* and *Dialium guineense*, which dominate in the upper stories. In drier parts, gallery forests have a well-marked boundary with the surrounding savanna/woodland. Phytogeographically, gallery forests in the Sudanian Region comprise a high percentage of species that mainly occur in the Guineo-Congolian rain forests. Among this group belong large, usually evergreen trees such as *Ceiba pentandra*, *Dialium guineense* and *Spathodea campanulata*. Further to the north, trees like *Anogeissus leiocarpa*, which are typical of savannas and woodlands, become frequent in gallery forests.

I-3.6.4 Mediterranean/Sahara transitional zone in Morocco

The oceanic, northwestern part of the Mediterranean/Sahara transitional zone was originally covered by woodlands dominated by *Argania spinosa*, *Juniperus oxycedrus* and *Quercus rotundifolia* trees and by succulent coastal scrubland with species of *Euphorbia* and *Kleinia*.

Oromediterranean steppes and debris vegetation characterize the vegetation belt above 2,500 m in the High Atlas (Quézel 1957). In many areas, these have replaced degraded *Juniperus thurifera* forests. Floristically, this vegetation type is characterized by thorny dwarf shrubs (e.g., *Alyssum spinosum, Bupleurum spinosum, Erinacea anthyllis, Vella mairei,* and *Astragalus ibrahimianus*), perennial grasses (e.g., *Festuca hystrix* and *Helictotrichon sedenense*), cushion plants (e.g., *Jurinea humilis* and *Catananche caespitosa*) and debris specialists (e.g., *Linaria tristis* and *Vicia glauca*). According to Fennane (2004), the High Atlas constitutes a regional center of endemism (comprising approx. 425 species and 60% Moroccan endemics). *Asteraceae*, *Fabaceae* and *Lamiaceae* belong to the families with a high number of endemic taxa.

Some scattered forest fragments dominated by *Quercus rotundifolia*, *Juniperus* sp. and, locally, *Pinus halepensis* still remain on the southern slopes of the Central High Atlas and the Saharan Atlas. Many elements of evergreen Mediterranean forest-ecosystems, e.g., the Mediterranean Fan Palm (*Chamaerops humilis*) and the Montpellier Maple (*Acer monspessulanum*), reach their southern limit in this area.

Steppes (mainly characterized by *Artemisia* spp., *Stipa* spp. and *Lygeum spartum*) prevail in cool arid environments down to 1,500 m. While sagebrush dominates to a large extent the degraded pastures, we often find codominance or dominance of perennial grasses on rural cemeteries. These patterns indicate an important contribution of permanent grasses to the potential natural vegetation of these steppes.

In spring, we find a species-rich guild of therophytes on the bare patches between dwarf shrubs and grass tufts. Many of these species either have a large distribution area in semi-arid and arid northern Africa and the Middle East, or they play a role in the weed flora of southern and south-central Europe.

In the warmer arid environments down to the northern limit of the Sahara, semideserts dominated by *Chenopodiaceae* (e.g., *Hammada scoparia* and *Fredolia aretiodes*) are of considerable importance. Shrubs like *Ziziphus lotus*, *Retama retam* or *Withania adpressa* are restricted to small wadis with some additional run-on water supply.

Of particular ecological importance is the alluvial vegetation along larger wadis with *Tamarix* spp. and *Nerium oleander* (e.g., in the Oued Drâa), which indicate access to phreatic water. Savanna-like ecosystems with Sahelian affinities, characterized by trees (e.g., *Acacia raddiana, A. ehenbergiana* and *Maerua crassifolia*) and permanent C4-grasses (e.g., *Pennisetum dichotomum* and *Panicum turgidum*), already belong to the Saharan biome.

Saharan dune ecosystems, so called ergs, host a specialized flora with *Calligonum polygonoides* and *C. azel*, *Stipagrostis pungens* and *Danthonia fragils*. The Roostertree (*Calotropis procera*) indicates ruderalized dune ecosystems close to settlements, kraals and wells. Salt pans are another important feature of the Saharan biome. These provide a habitat to a specialized halophytic flora with many species from the families *Chenopodiaceae*, *Plumbaginaceae*, *Frankeniaceae* and *Brassicaceae*.

While the ratio of endemism increases with altitude, total species density culminates at mid altitudes (see sect. I-7.1) and declines with increasing altitude and aridity. Heterogeneity in the vegetation increases from semiarid steppes to arid ecosystems. In the High Atlas, biomass productivity culminates in summer due to low temperatures from autumn to spring. This summer maximum of productivity changes southwards to a bimodal productivity pattern with maxima in spring and autumn that are controlled by an increasingly bimodal precipitation regime (see sect. I-4.2). The total standing biomass decreases dramatically from oromediterranean steppes to arid semideserts. The overall high grazing pressure of small ruminants leads to a homogenization of the vegetation, thus reducing ß-diversity at the landscape level.

I-3.7 Political and administrative structures: History and present situation

G. Menz

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The political and administrative histories of West and Northwest Africa are long and complex, including at least five major periods. First, in prehistory, the first human inhabitants arrived, developed agriculture, and made contact with peoples to the north. In the second period, the Iron Age empires developed centralized states and consolidated both intra- and extra-African trade. The third period saw major political city-states flourishing in the region. These states had an extensive association with non-Africans, including the African slave trade. The fourth period was a brief colonial period, in which Great Britain and France controlled almost the entire region. The current nations were formed during the fifth period, which is termed the post-independence era (Molifu 2007, personal communication).

3.7.1 Colonial period

In the early nineteenth century, a series of Fulani reformists swept across western Africa. The most notable of these was Usman dan Fodio and his Fulani Empire, which replaced the Hausa city-states in the Sahel regions of Nigeria and Niger (Davidson 1995). France and Britain continued to advance, however, during what has been termed the 'scramble for Africa,' in which kingdom after kingdom in the region was subjugated under colonial control. With the fall of the Ashanti queen Yaa Asantewaa in 1902, most West African military resistance to colonial rule came to an effective end. Britain controlled Gambia, Sierra Leone, Ghana and Nigeria throughout the colonial era, while France unified Senegal, Guinea, Mali, Burkina Faso, Benin, Ivory Coast and Niger into French West Africa. Portugal founded the colony of Guinea-Bissau while Germany claimed Togoland, a colony that was divided between France and Britain following the First World War. In West Africa, only Liberia retained its independence, though at the price of a number of territorial concessions (see fig. I-3.7.1).

I-3.7.2 Postcolonial era

Following the Second World War, nationalist movements arose across West and Northwest Africa. In 1956, Morocco became independent from Spain. One year later, Ghana became the first sub-Saharan colony to achieve its independence, followed the next year by the French colonies. By 1974, West Africa's nations were entirely autonomous (Davidson 1995).

Since their independence, many West African nations have been plagued by corruption and instability accompanied by notable civil wars (e.g., Nigeria, Sierra Leone or Ivory Coast) and a succession of military coups in Ghana and Burkina Faso. Many states have failed to develop their economies despite enviable natural re-

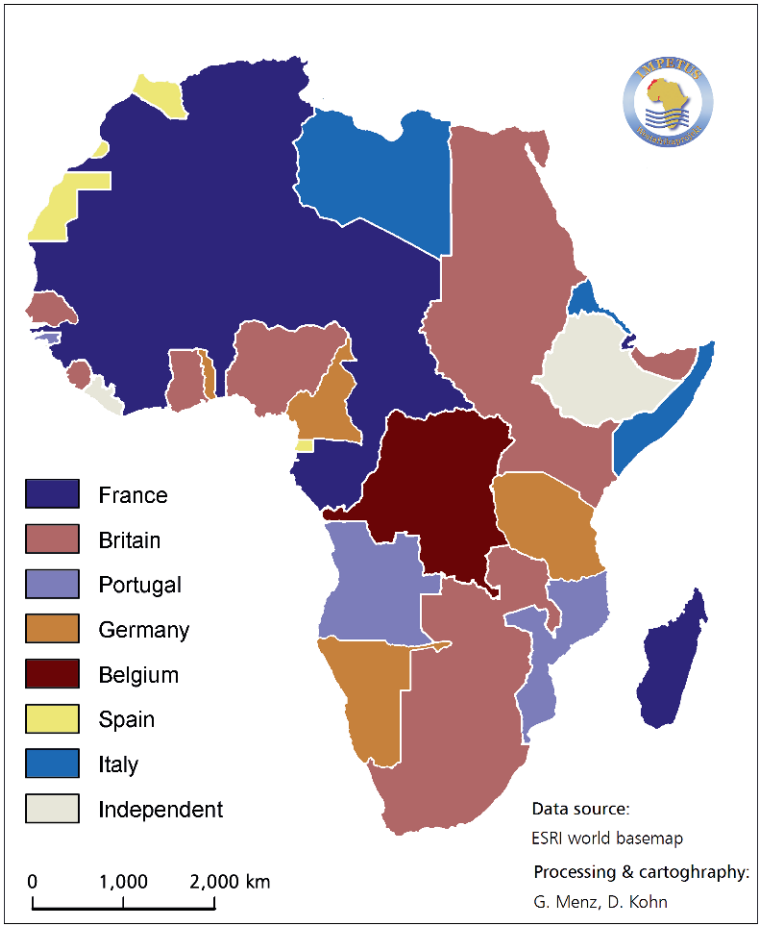

Fig. I-3.7.1: European territorial claims on the African continent in 1914 (Source: Modified after McCullough 2003).

sources, and political instability is often accompanied by undemocratic government. Until recently, most governments in West Africa were illiberal and partially corrupt. Several countries have been plagued with political coups, ethnic violence and oppressive dictators. Since the end of colonialism, the region has been the stage for some of the most brutal conflicts ever to erupt. Though a few countries like Ghana and Senegal have enjoyed relative stability and have even seen some growth, all forms of progress in West and Northwest Africa are contingent on the efficiency and justness of governance and the fair allocation of resources.

Today, Africa contains 53 independent and sovereign countries, most of which still have the borders drawn during the era of European colonialism (see fig. I-3.7.2).



Fig. I-3.7.2: Political map of the African continent with its 53 sovereign countries (Source: Modified after Gaba 2008).

The vast majority of African countries are republican and operate under some form of presidential system of rule. However, a few of them have instead cycled through a series of coups that have produced military dictatorships.

While Benin has built up a multiparty democracy since 1960, Morocco has been a constitutional monarchy since its independence from Spain in 1956 (see table I-3.7.1).

Table I-3.7.1: Fact sheets for the Republic of Benin and the Kingdom of Morocco (Source: CIA 2009b).

	Benin	**Morocco**
Capital	Porto-Novo (6°28′N, 2°36′E)	Rabat (34°02′N, 6°51′W)
Largest city	Cotonou	Casablanca
Official languages	French, Vernacular Fon, Yoruba	Arabic, French
Government	Multiparty democracy President Yayi Boni	Constitutional monarchy King Mohammed VI Prime Minister Abbas El Fassi
History	Independence from France since August 1, 1960	Unification 1554 Unified by Saadi dynasty 1554 Alaouite dynasty (present) 1666 Independence from France March 2, 1956 Independence from Spain April 7, 1956
Area	Total 112,622 km²	Total 446,550 km²
Population	2009 estimate 8,935,000 2002 census 6,769,914 Density 79.3/km²	2009 estimate 31,993,000 2004 census 29,680,069 Density 71.6/km²
Ethnic groups	Fon or Dahomeyans 25%, Adja 6%, Aizo 5%, Goun 11%, Bariba 12% Yoruba 12%, Somba 4%, Fulani 6%, Holli, Dendi, Pilapila and others 19%	Arab-Berber 99.1%, other 0.7%, Jewish 0.2%
GDP (nominal [1])	2008 estimate Total $6.712 billion Per capita $828	2008 estimate Total $88.879 billion Per capita $2,827
HDI [2] (2007)	0.492	0.654
Currency	West African CFA franc (XOF)	Moroccan dirham (MAD)

[1] Current exchange rate method converts the value of goods and services using global currency exchange rates.

[2] Human Development Index of the United Nations Development Program

I-3.8 Population, ethnicity, and religion

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Although West and Northwest Africa have very distinct societies, they show some common features, such as their young populations. In both regions, the population is unevenly distributed and highly dynamic. While growth rates in Northwest Africa are decreasing, West Africa still has very high growth rates. Benin is characterized by interior migration, while urbanization and out-migration play an important role in Morocco. The societies of both regions are culturally diverse. Benin's population can be divided into more than 50 ethnic groups (*Institut National de la Statistique et de l'Analyse Economique* (INSAE) 2003), with almost as many languages. The religious identities are also diverse and hybrid between African religions, Christianity and Islam. In contrast, 98.7% of Moroccans are Muslims (Central Intelligence Agency (CIA) 2009a). But with its Berber and Arabic speaking populations, Morocco is characterized by cultural and linguistic diversity.

I-3.8.1 West and Northwest Africa

The societies of West Africa and Northwest Africa differ on many accounts, and it would fill pages to map out the differences in detail. However, there are also commonalities of social and cultural development in these two sub-regions of the continent. Both regions have very young populations, with major percentages of the population under fifteen years (43.3% in West Africa in 2005; United Nations (UN) 2008). The commonalities of demographic structures may decrease in years to come as population growth rates today differ significantly. While growth rates are still high in West Africa (2.54), they are much lower in Northwest Africa (1.70; UN 2008). Demographic scenarios for the period 2020-2025 show that although there is a general decrease in population growth in both regions, Northwest Africa will approach a European growth pattern (1.22) while West Africa will still have a sizeable growth rate of 1.96% (UN 2008). By 2025, the total population of West Africa will increase from some 269,990,000 to 422,733,000 while Northwest Africa's population will grow from 195,444,000 to 263,120,000. In many countries of West and Northwest Africa, this population is very unevenly distributed due to varying climatic conditions, especially the presence of water. The population distri-

bution is also uneven for historical and economic reasons (see fig. I-3.8.1). The population of West Africa is extremely heterogeneous in terms of ethnicity, language and religion while Northwest Africa shows more homogeneity in these variables. Urbanization rates in both regions are high. By 2025, urbanization will increase in West Africa from 41.7% of the population to 53.5% and in northern Africa from 50.2% to 58.6% (UN 2007). This entails complex patterns of migration and

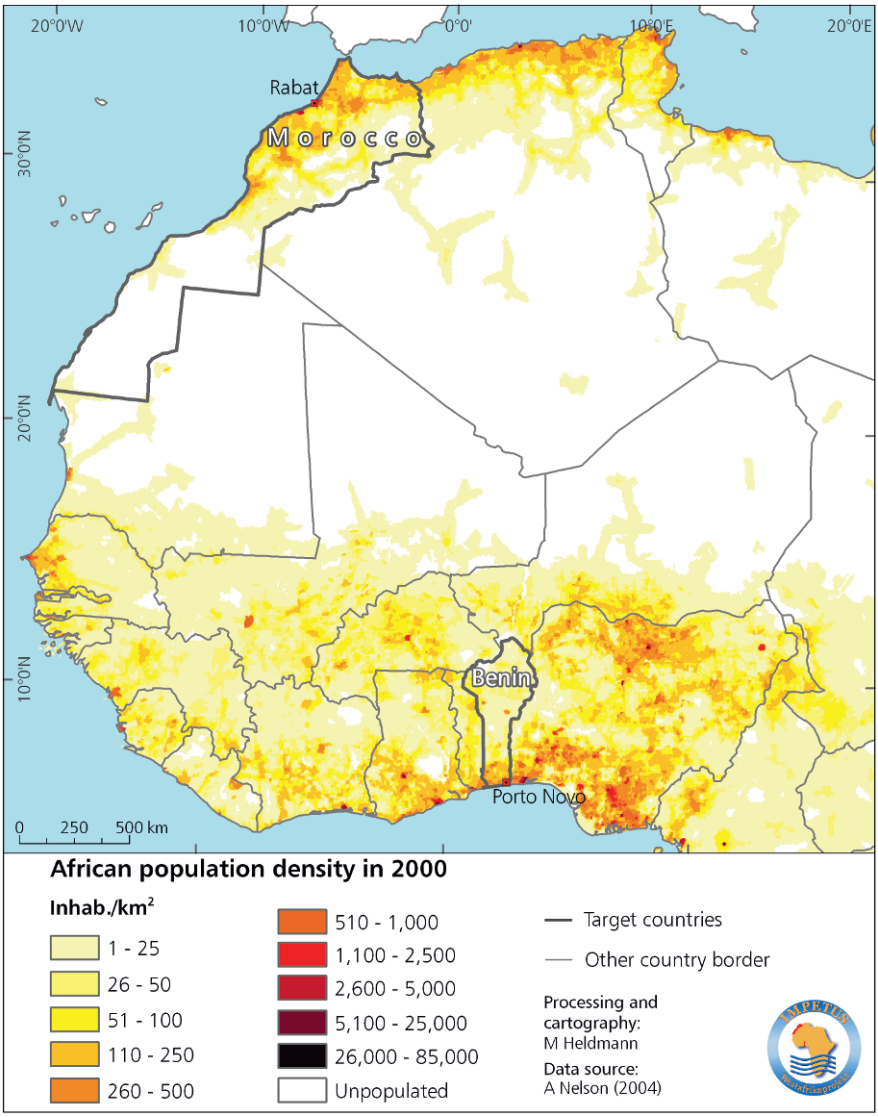

Fig. I-3.8.1: Population density in West and Northwest Africa in the year 2000 (Data source: Nelson 2004).

rural-urban interactions in both regions, and we will show in the chapters to come that these demographic dynamics impact local, rural, social-ecological systems profoundly (see also sect. II-3.4).

All North African countries are classed in the 'Middle Human Development Group' while most of the West African countries are in the 'Low Human Development countries' class, except Ghana and Senegal. GDP (Gross Domestic Product) growth rates for 2008 range between 0.8% (Togo) and 7.5% (Liberia) with Benin 4.8% and Morocco 5.9%, the focal countries of this book, being in the middle range (United Nations Development Programme (UNDP) 2009).

The following two chapters will flesh out social and cultural data on both focal countries in more detail.

I-3.8.2 Benin

With 6.8 million inhabitants in 2002 (INSAE 2003) and an estimated population of 8.0 million in 2008 (IMPETUS), Benin is dwarfed by its giant neighbor, Nigeria. Nigeria has the largest population of the continent, with approximately 144.7 million inhabitants in 2006 (The Worldbank Group 2008a) and with a larger population in the Lagos agglomeration than in the whole of Benin. Still, demographic growth in Benin is relatively high and has increased from 2.8% between 1979 and 1992 to 3.3% between 1992 and 2002, compared to only 2.6% for sub-Saharan Africa in 2000 (The Worldbank Group 2008b). Like all West African countries, Benin has a very young population, with nearly half of the population under fifteen years old. Although fertility rates have decreased from 6.1 children per woman in 1992 to 5.5 in 2002, they are still at a high level (INSAE 2003). Furthermore, life expectancy has grown from 54.2 years to 58.2 years for the same period.

The overall population density in Benin is 60 inhabitants/km², but the demographic structure is characterized by strong spatial disparities of population growth, density and dynamics. Southern Benin (238 inhabitants/km²) has much higher population densities than Central and North Benin (27 inhabitants/km²). The density is highest in Cotonou (8,100 inhabitants/km²) and still extremely high in its peri-urban surroundings (950 inhabitants/km²), which are now the main destination for migrants to the Cotonou metropolitan area. These peri-urban areas reach growth rates of 10% per year. The demographic weight of southern Benin is heavy: 60% of the total population lives here on 20% of the national territory (see fig. I-3.8.2). However, rural areas in southern Benin now have decreasing growth rates due to migration to the suburban surroundings of Cotonou and to less densely populated rural areas in Central and North Benin (Doevenspeck 2005). In these regions, the population density is below 70 inhabitants/km², with the exception of Parakou. Densities below 10 inhabitants/km² are reported for the extreme north of the country. The region around Ouaké and Boukoumbé in the northwest has higher population densities (70 and 50 inhabitants/km²), but lower growth rates because of

emigration to these parts of Central Benin. These areas, such as Tchaourou, Ouèssè and N'Dali, are the major destination for agricultural colonization.

Benin is characterized by a pronounced ethnic, linguistic, social and regional diversity. Of course, official census data cannot give insight into the dynamics and ambiguities of ethnicity. According to the national census database (INSAE 2003), the south of Benin, which is the territory of the former Danhomè kingdom, is dom-

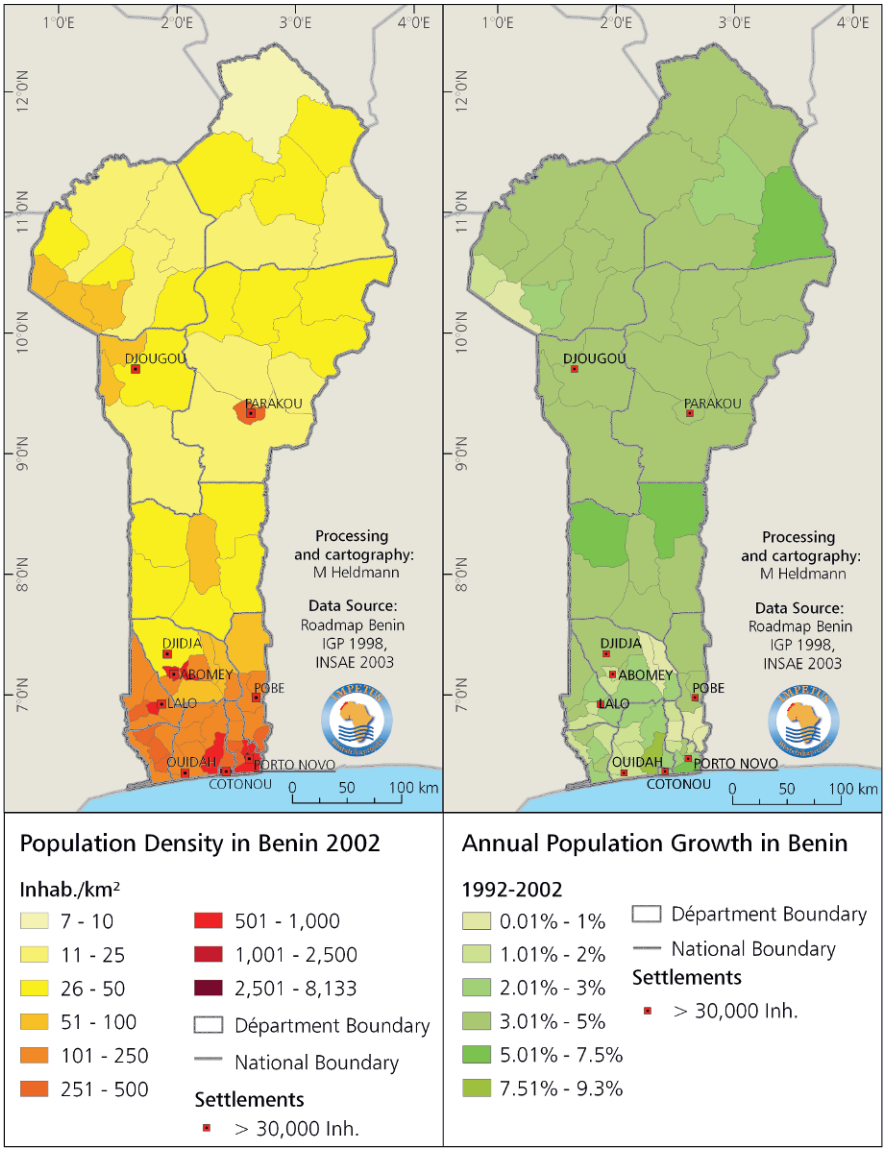

Fig. I-3.8.2: Population density and growth in Benin 2002.

inated by the Fon population. The southwest is characterized by a strong representation of Adja and related groups while the Yoruba live mainly in the southeast. Large parts of Central Benin are ethnically fragmented. Close to the Togo border, the Yom and the Lokpa constitute the majority of the population. In the northeast, the Bariba are dominant. At the time of the slave raids, the region of the Atacora Mountains in the northwest of Benin historically had the function of providing a retreat for the Gurmanché and Betamaribé communities, and to the present day, both ethnic groups constitute the ethnic majority in this region. According to the national population census, the northern frontier up to Niger is dominated by households with Dendi affiliation.

Attention should be paid to the fact that the sample of people interviewed by the national census is mainly composed of male household heads. Beninese households and villages are characterized by a multiethnic composition. Across the wide spread of ethnic affiliations, the population of Benin shares some dominant cultural patterns. Among them are pronounced social and political hierarchies in rural and urban areas. Here there are gerontocratic rules of respect and power as well as rules of descent according to patrilinear affiliation.

Quantitative, spatialized data based on the National Population Census (INSAE 2003) are available on religion. According to the census, 42.7% of the Beninese call themselves Christian, followed by 42.4% Muslims. While Christians are predominant in large parts of South Benin, North Benin is mainly inhabited by Muslims. Christians are subdivided into numerous denominations. Catholicism is still the largest group, but different Protestant groups and other African churches, such as the Celestial Church of Christ, have gained in prominence recently.

Only 23.3% of interrogated persons claimed to be followers of traditional religions (17.3% Vodoun, 5.9% other). Other official quantitative data (e.g., *Internationale Weiterbildung und Entwicklung gGMBH, Archives Nationales du Benin*, CIA World Factbook, see Hadjer 2006) show clear limitations when it comes to describing the complexities of religious affiliation. Religious affiliation is often described in a monolithic way: one person, one religion. Quantitative surveys carried out by IMPETUS reveal the same tendency. At the village level, e.g., Bougou, 89% of household heads reported that they were Moslems, 6% Christians and only 2% named “other beliefs”. In a neighboring village, almost nobody chose the category “other beliefs,” even though the village is known as one of the most important centers of secret societies (Hadjer 2006). We assert that hybrid synergies between different religious beliefs are a major feature of religious identities in Benin. In this respect, anthropological research conducted by IMPETUS offers a more differentiated view on religious identities in Benin. Qualitative interviews and other anthropological techniques disclose a complex world of hybridism between religions like Vodoun, Islam, and Christianity with ancestor worship, belief in spirits, witchcraft, and other occult practices (Hadjer 2008).

I-3.8.3 Morocco

The total population of Morocco is much larger than Benin's. According to the 2004 census, the national population totaled 29.8 million people. Population projections by the Moroccan *Haut Commissariat au Plan* (HCP) give population figures of about 31.5 million for 2009 (HCP 2009). Demographic growth rates show a converse development compared to Benin. The rate is continuously declining,

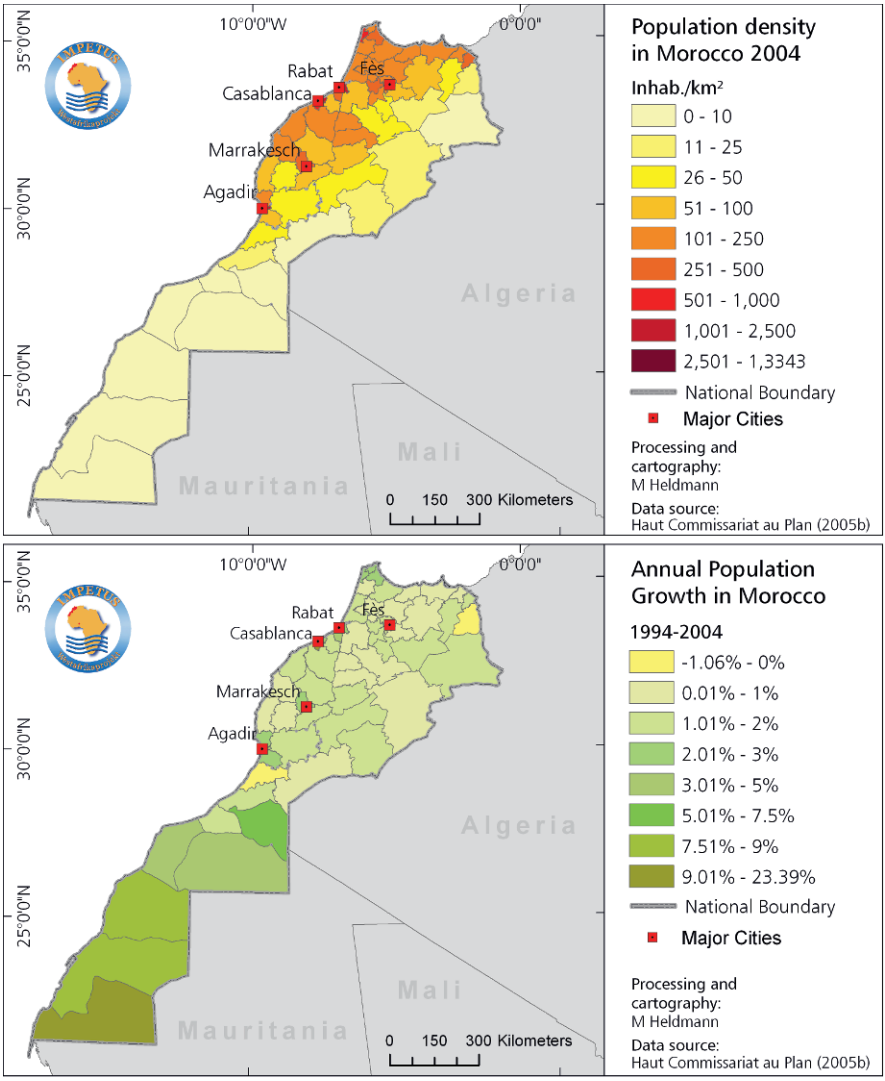

Fig. I-3.8.3: Population density and growth in Morocco 2004.

from 2.8% p.a. between 1960 and 1971 to 1.4% between 2006 and 2007 (HCP 2007). Some areas of Morocco even have negative growth rates, while higher rates can be observed in the sparsely populated Western Sahara region and in major urban centers (see fig. I-3.8.3). The decreasing rate of population growth can be partly credited to declining fertility rates, but must also be attributed to emigration. The impact of both components considerably differs between urban and rural milieus. In the rural areas, there are large emigration movements, but higher natality and fertility rates. Profiteers of the migration movements are the already urbanized regions of Morocco, particularly in the north of the country and, to a lesser extent, Europe and the Middle East (see Rössler et al. in sub-subsect. I-8.1.2.2). Nevertheless, the impact of migration on population development is difficult to estimate because reliable figures that consider all types of migration do not exist.

Out-migration from rural areas is only partly compensated for by the considerably higher fertility rates of rural areas. Fertility in rural areas was 4.25 children per woman in 1994 against 2.56 children per woman in urban areas (*Direction de la Statistique* 1995). Nevertheless, the fertility gap is narrowing, and in 2004, the rate had fallen to 2.05 children per woman in urban areas and 3.06 children per woman in rural areas. For all of Morocco, the rate declined from 3.28 children per woman in 1994 to 2.33 children in 2007 (*Haut-Commissariat au Plan* (HCP) 2007).

This development is mirrored in changes in the population pyramid. In 1960, the pyramid had a broad base, with 19% of the total population being between 0 and 4 years old and 44.4% younger than 15 years. Since then, this rate has been reduced. In 1982, 15.2% of the total population was between 0 and 4 years old and 42.3% younger than 15, while in 2007, only 8.4% belonged to the youngest age group and a total of 29.2% of the population was younger than 15 years. The increasing life expectancy also changed the structure of the population pyramid. In 1994, an average man lived 66.3 years and an average woman lived 69.4 years. Since then, life expectancy has risen to 71.2 years for men and 73.7 years for women (HCP 2007).

The overall population density in Morocco is 43.6 inhabitants per km², but the population is very unevenly distributed over the country (see fig. I-3.8.3). Especially in the arid and less developed southern provinces known as Western Sahara, there are very low population densities of less than 5 inhabitants/km². Unlike the extreme south, the lowlands in the north and between the Atlantic Ocean and the Atlas Mountains are fertile and relatively well developed. Together with the industrialized urban conglomerations surrounding Casablanca and other northern and coastal cities, they form the economic backbone of the country. On a general level, these areas and the adjacent provinces are densely populated, with a range of 200 inhabitants per km². The population density is highest in Casablanca province, where 2.9 million people live on 220 km², representing more than 13,000 inhabitants per km². Also, the peri-urban surroundings of Mohammedia, Mediouna and Nouaceur, which for a long time have been main destinations for migrants to the greater Casablanca-agglomeration, show high population densities (958 inhabitants/km²).

In addition, the provinces surrounding the cities of Tangier, Fés, Rabat and Agadir are centers of a comparably high population density. The provinces of Oujda in the north (260 inhabitants/km²) and Marrakesh in central Morocco (411 inhabitants/km²) could be considered secondary population centers.

The more arid and infrastructural remote provinces of the hinterland show population densities of less than 50 inhabitants/km², on average. These regions, which have long been economically marginalized, comprise the mountainous areas and the region south and southeast of the Atlas Mountain chain. The demographic weight of the northern coastal region is heavy: 61% of the total population lives on 13% of the national territory (including the Western Sahara).

In 2007, Morocco's GDP per capita was $3,800, with an annual growth rate of 2.1%. Today, tourism accounts for Morocco's largest source of foreign revenue, followed by remittances by Moroccan workers abroad.

The religious situation in Morocco is quite homogeneous. Muslims, mostly of the Sunnite branch, make up 99% of the population. Christians and Jews only form small minorities.

Culturally and linguistically, Morocco is divided between an Arabic and a Berber speaking population. Approximately 12 million (40% of the population), mostly in rural areas, speak one of the three different Berber dialects (Tarifit, Tashelhiyt, and Tamazight). On the regional and local levels, there are further ethnic diversifications within the two major linguistic groups, which are historically grounded. The Berber population, especially, is highly fragmented. Until the French 'pacification', this fragmentation had caused many internal conflicts as well as conflicts with neighboring Arabic speaking groups. Currently, Arabic is the official language of Morocco, while French is often the language of business, government, education and diplomacy. The several Berber dialects were only recently officially acknowledged and included in school curricula.

I-3.9 Economy and infrastructure

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This section aims to illustrate the economic background of water-related issues in Benin and Morocco. Table I-3.9.1 provides an overview of key indicators regarding the economy and infrastructure of Morocco and Benin in the wider context of the regions in which they are located. These are Morocco in the Maghreb (with Algeria and Tunisia) and Benin in West Africa, which is a group of fifteen countries south of the Sahara.

With few exceptions, both countries are typical for their regional context, but there are pronounced differences between Northwest and West Africa. Morocco, for example, has a middle-income economy that slightly lags behind resource-rich Algeria and Tunisia. Benin is found, together with many other West African countries, among the poorest countries of the world. While water supply and access to sanitation have improved much in recent years, the lack of paved roads presents a major burden, particularly for Benin's rural economy. The economic potential of the two countries to deal with the consequences of resource scarcity and Climate Change is discussed in more detail below.

Table I-3.9.1: Economic and infrastructure indicators for Morocco and Benin in their regional context (Source: World Bank 2008).

	Morocco	N-W-Africa	Benin	W-Africa
GDP per capita (constant[3] 2000 US$)[1]	1,297	1,814	321	300
GDP growth (annual %)[1]	3.7	4.2	4.2	3.4
GDP growth per capita (annual %)[1]	2.1	2.8	1.0	1.2
Agriculture, value added (% of GDP)[1]	15.4	12.3	33.7	36.1
Improved water source[2] (2004)	81.0	86.3	67.0	61.4
Improved sanitation facilities[2] (2004)	73.0	83.3	33.0	33.5
Roads, paved (% of total roads, 2004)	56.9	64.3	9.5	24.9

[1] Average of the years 2000–2005

[2] Percent of population with access

[3] Constant US$: values corrected for changes in the purchasing power of the US Dollar over time

I-3.9.1 Benin

With an average per-capita income of 321 USD in 2006, Benin is one of the poorest countries in the world. This is also reflected in its low ranking in the Human Development Index (HDI) where it is placed 163rd out of 177 countries (World Bank 2008). Since 2000, economic growth rates for the entire economy moved between 2.9 (2005) and 6.2% (2001), with a tendency toward accelerating growth since 2005 and an expected growth rate of almost 5% for 2008 (OECD 2007). Even though the recent growth history of Benin is more positive and stable than the West African average, a population growth rate that is still slightly over 3% per year has reduced progress in per-capita income to a tantalizing 1.3% average in the new millennium. Consequently, the monetary poverty rate[1] is high, at 38% (World Bank 2008).

Benin's economy is largely dependent on agriculture, forestry, livestock and fisheries (36% of GDP[2]), with cotton as the major export crop. The second important private sector of the economy is services (37% of GDP) with trade in particular: the port of Cotonou as well as Benin's role as a transit country are important sources of revenue. Public services contribute 12% to the GDP, pushing the entire service sector to almost 50% of the GDP (OECD 2007). Consequently, manufacturing, energy, and construction only account for 14%, exhibiting a notable weakness in the secondary sector's development. Foreign exchange is earned primarily from exports of cotton products (~ 77% on average from 1992 to 2003) and cashew nuts (6%). Non-agricultural exports only account for 16% of total exports (Linjouom 2007). Imports consist mainly of fuel and electricity (20%), and food (22% on average).

The total expenditure of the central government represented 21.4% of GDP in 2006. Of these total expenditures, investment made up roughly 23%. Of all public investments through 2000-2006, the majority went into infrastructure projects (43.4%), including investments in the water sector. Over this period, the financing of public investments absorbed almost 70% of the grants and loans from foreign donors (IMF 2008).

[1] Households with an annual income of less than 125 € per person are defined as monetarily poor.

[2] GDP (Gross Domestic Product) is the value of all goods and services of produced domestically within a reference period.

I-3.9.2 Morocco

Morocco's gross national product (GDP) was 51 billion USD in 2005, with a GDP per capita of slightly more than 1,350 USD (constant 2000 USD; World Bank 2007). The economy has increased constantly over the last few years, but with highly volatile growth rates (see fig. I-3.9.1). Comparing the per-capita growth of Morocco and Benin over time shows that the lower population growth rate in Morocco enables the country to gain a much higher per-capita growth of national income. This also becomes obvious when looking at the growth of gross national income[3] (GNI) in Benin and Morocco in table I-3.9.1. The sectoral composition of Morocco's economy is almost equally split among tourism, agriculture, and manufacturing. The agricultural sector experienced a 30% growth in 2006, mainly driven by an outstanding cereal harvest in 2006 and improvements in livestock production. The secondary and tertiary sectors also experienced positive growth rates of 5% each. The tourism sector, especially, is booming thanks to foreign investment in tourist regions such as Marrakech and Tangier (OECD 2007).

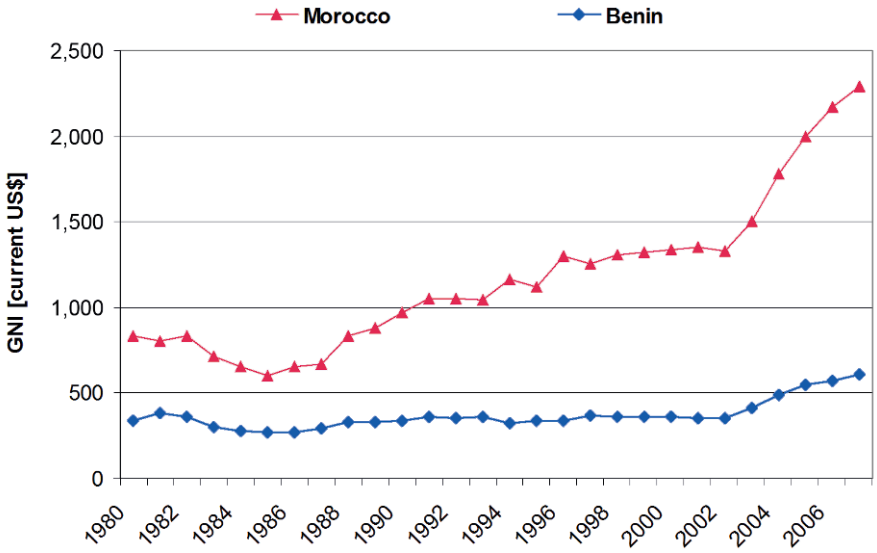

Fig. I-3.9.1: Gross national income per-capita in current US$, 1980-2007 (Source: World Bank 2008).

[3] GDP and GNI only slightly differ from each other. GDP focuses on the productive strength of an economy while GNI informs how this strength is transformed into national income by additionally accounting for the net payment flows with other countries.

In the Human Development Index (HDI), Morocco is ranked 126th among 177 countries. Two percent of the population live below the poverty line of 1 dollar per person per day, 14% of the population live with less than 2 dollars per day, and 19% of the population live below the national poverty line (UNDP 2007/2008). Morocco still devotes nearly 15% of total public expenditures to national defense, though this fraction has decreased in recent years as education and health issues have gained in importance (IMF 2005). The budget deficit stood at 5.1% of the GDP in 2006, which represents a reduction in comparison to previous years. Public debt decreased from 75 to 70% of GDP in 2006.

As Morocco is located in water-scarce North Africa, preserving available water resources is a focus of the country's development strategies. In urban areas, 92% of the population hasve access to safe drinking water. In rural areas, this rate is much lower, with 56% in 2005. As compared to other North African countries, Morocco faces a need to catch up in the area of rural water and sanitation facilities (OECD 2007). Approximately 15% of Morocco's total cropland are irrigated (World Bank 2007). The government aims to expand the irrigated area by 10,000 hectares per year to make the sector more competitive in the face of mounting agricultural imports as a consequence of a liberalized external trade regime. Furthermore, areas of crops which demand relatively more irrigation water per unit value of output are intended to be reduced in the future. The focus will shift instead to fruits and perennial crops, such as olives, almonds, and dates, where the government renders support through subsidies and special loan programs.

The economic dimensions of water problems in West and Northwest Africa, their remedies, and the potential to deal with these problems appropriately differ to a wide extent between the two countries. Morocco, due to its geographical location and demographic characteristics, faces absolute water scarcity in terms of available renewable water resources per capita. At the same time, water is an important production factor, particularly in irrigation agriculture, which has long been subject to management practices and policies. For centuries, Morocco has had to invest in water infrastructure and, thanks to its status as a middle-income economy, now has an acceptable water provision network in urban areas and functioning irrigation perimeters at its disposition. On the other hand, this relatively high level of infrastructure development together with possibly worsening climatic conditions will make necessary improvements in water availability and efficiency all the more expensive. Morocco's geographical position is also reason for hope: its proximity to Europe will allow for increasing trade in agricultural products and tourism services as well as, for instance, electricity from solar energy.

Benin's water problems, by contrast, do not primarily originate from physical water scarcity but from the low economic potential of Benin to make these resources available. Priority in infrastructure development is given to drinking water supply and sanitation for private households. Due to Benin's economic weakness, the majority of necessary investments in water infrastructure currently is, and will have to be, financed directly or indirectly through foreign aid. Moreover, the rapidly rising population in Benin represents a major challenge for infrastructure de-

velopers. Water provision and efficiency considerations for agricultural production are, so far, less relevant. However, supplementary irrigation may become an issue in the near future, particularly when land scarcity will necessitate a shift from area expansion to crop yield increase (see chap. I-7).

I-3.10 Agriculture and food

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Agriculture can be defined as an alternating periodic process of diluting (e.g., sowing) and concentrating (e.g., harvesting) resources. Agricultural systems in West and Northwest Africa are characterized by a wealth of various dilution-concentration processes, each representing a specific signature of humankind attempting to secure a sustainable food supply in a given environment.

I-3.10.1 Crossing the Tropic of Cancer from the Mediterranean coastal lands to tropical Africa

Agricultural systems as well as the environmental conditions of agricultural activities are very diverse in West and Northwest Africa. The main agricultural producers and exporters here are Morocco in the Mediterranean Northwest African region, and Nigeria, Ghana, and Ivory Coast in the semi-humid to humid West African coastal area (see fig. I-3.10.1; Van-Chi-Bonnardel 1996; Raemaekers 2001; Dixon et al. 2001; FAO 2009). In Northwest Africa, agriculture changes from a Mediterranean agriculture along the Northwest African coast to a hill agriculture in the Rif and Atlas Mountains, within which, valleys have been transformed into fertile man-made irrigation perimeters. The Sahara region across Morocco, Algeria, Tunisia, Mauritania, Senegal, Mali, and Niger presents a great divide, not only in terms of climate, but also in terms of agriculture. Exceptions are northern and southern fringes, where some very extensive and seasonal nomadic grazing can be observed according to the seasonal opportunities provided by erratic rangeland pastures. Agriculture re-emerges on the southern side of the Sahara, enabled by two great river basins emerging from the Fouta Djallon Mountains. These are the Senegal river and the Niger river, which embrace the central and southern parts of West Africa. Both the Niger and Senegal rivers determine West African agriculture in combination with monsoonal influences from the Gulf of Guinea. The seasonal and spatial distribution of precipitation is of elementary importance for agricultural activity, which is a predominantly rainfed agriculture. In the humid coastal areas, agriculture has evolved from an export-dominated agriculture, with crops like coffee, cocoa, rubber, oil palm, cotton, peanut, pineapple, banana and forest products, into a combination of the same export crops with food crops like maize, cassava, yam, sweet potato, sorghum, rice, and various pulses and vegetables, which

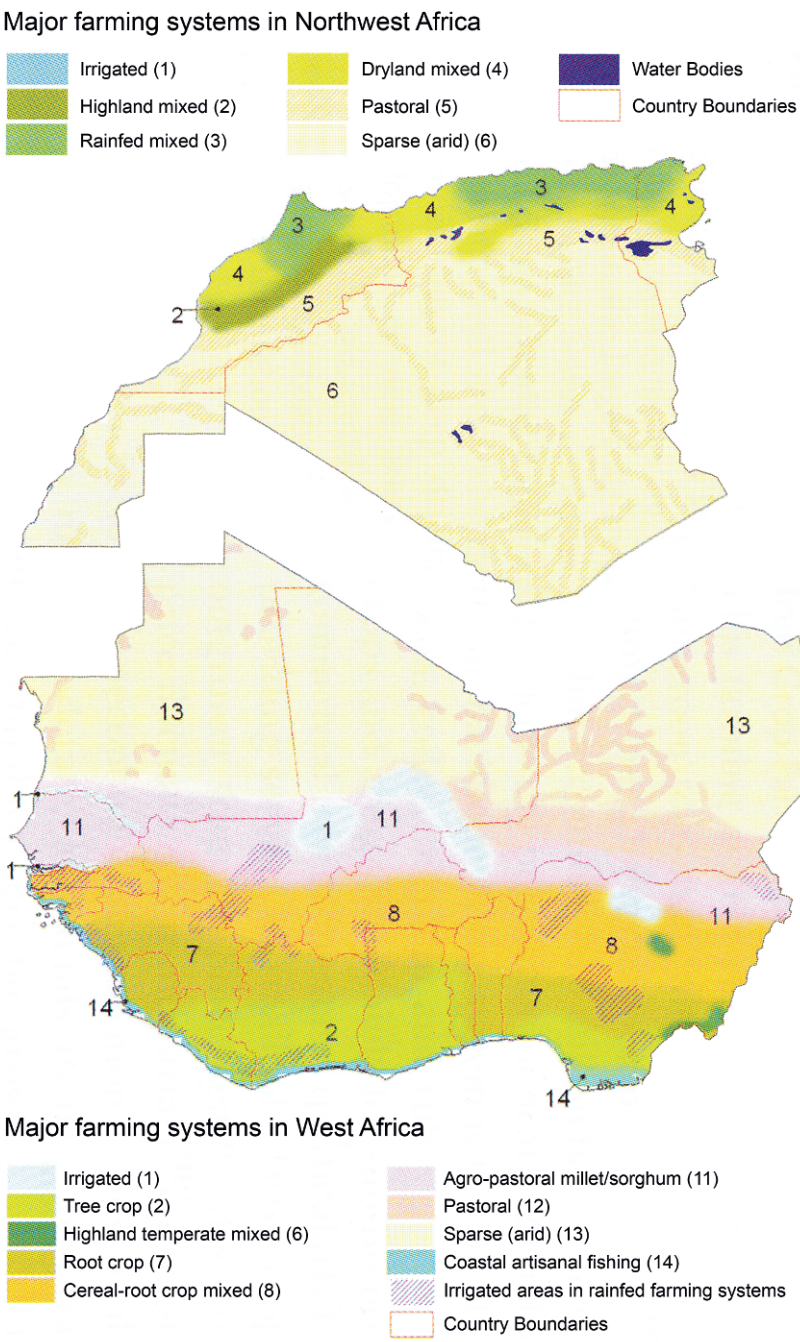

Fig. I-3.10.1: Major farming systems in Northwest and West Africa (Source: Modified from Dixon et al. 2001).

are increasingly oriented toward rising urban markets. Traditional subsistence agriculture is disappearing. The whole of sub-Saharan agriculture is encroaching on the remaining forest and savannah vegetation in its efforts to collect dearly wanted soil fertility. Apart from a very few natural parks and sacred sites, most of the original forest has been converted into savannah, if not agricultural land. Some state-supported crops, like cotton or peanut, will tend to concentrate production factors more efficiently, but being the sole intensive crop in the crop rotation, some of its inputs are diverted to other crops. The interaction between animal husbandry of semi-nomadic nature with settled agriculture is poor. In fact, classical shifting cultivation (Jurion and Henry 1967) has disappeared almost entirely from the region. It has now been replaced by soil fertility restoration through crop-fallow rotation.

I-3.10.2 Benin

In Benin, agriculture has an elementary social and economic meaning (see sect. I-3.9). Cotton is the most important cash crop. Other common cash crops are oil palm, groundnut, cashew, or pineapple. Directly and indirectly, agriculture gives work and income for the majority (around 80%) of the population (Igué 2000). In Benin, traditional farming systems are still dominant, and they generate the majority of agricultural products (Igué 2000). Subsistence-driven smallholders usually cultivate crops like maize, yam, sorghum, bean, millet, or cassava with low capital inputs (traditional tools and seldom use of fertilizers or irrigation) and with little mechanization, mainly for their own consumption (Igué 2000; Cenatel 2002; Mulindabigwi 2006). Crops like rice, mango, groundnut, or cashew are generally grown for marketing purposes. Food crop fields account for at least 60% of the total cropland (Igué 2000).

In such traditional systems, yields depend strongly on the available biophysical conditions as farmers lack the capital to compensate for natural constraints. In Benin, only 6,000 ha are irrigated (CENATEL 2002). In general, the biophysical conditions are moderate (Igué et al. 2004; Röhrig 2008; Röhrig and Laudien 2009). This restricted suitability for agricultural land use results mainly from a rather low chemical fertility and unfavorable physical characteristics of the soils as well as a limited and variable vegetation period. Yields are generally low, as soil fertility declines rapidly after several years of cultivation with sustainable technology remaining beyond reach (Junge 2004; Mulindabigwi 2006). In the north, fields can be cultivated three to four years, and in the center and in the south, up to nine years, although in the latter case, soil fertility declines rapidly (Igué 2000; Mulindabigwi 2006; Röhrig 2008). Traditionally, bush fires, alternation of crops and fallow systems are used to increase soil fertility. This causes an excessive use of space and an undesirable impact on natural resources (Igué 2000; sect. I-7.1). In addition, farmers minimize risks by cultivating several small fields (1-5 ha) within a specific area in order to cope with rainfall variability and low levels of yield

(Akapi 2002; Mulindabigwi 2006). Neumann et al. (2004) have stated that nearly all areas of Benin are included within a crop-fallow cycle, and only marginal sites, such as steep slopes, are completely devoid of agricultural use.

Increased population pressure has led to typical changes in the traditional farming system in Benin. During the 'phase of expansion,' agricultural activities are spatially extended to raise the general food production, transferring natural vegetation cover into fields. This process is predominant as long as forests and woodland are available for transformation into fields. In Benin, 11% of the woodlands and forests were cleared between 1984 and 1994 (World Resource Institute 1998, cited in Wezel and Böcker 2000), whereas mosaics of cultivation and bush fallow increased between 1978 and 1997 by 223% (Igué 2000). Recently, this process has been noticeably widespread in the middle and northern parts of Benin. On the positive side, there is an increasing importance of tree crops like cashew and teak. When suitable land resource becomes scarce, agricultural activities are expanded into marginal sites. This process is observable in southern areas (Weller 2002; Igué et al. 2004).

The following 'phase of intensification' is characterized by decreasing years of fallow to permanent cultivation. During this phase, the productivity of land and labor decreases progressively, and land degradation becomes apparent unless appropriate technologies are introduced. Rising population pressure together with access to markets are the driving forces that determine the intensification processes of agricultural activities if other economic alternatives are lacking (Igué 2000). The latter can be observed mainly in the south and in sites where cash crops, particularly cotton and rice, are cultivated. Examples of intensification are the increasing use of plowing tools in Central and northern Benin and the use of fertilizers for cotton. Population-driven intensification, however, can be observed nearly overall (Wezel and Böcker 2000; CENATEL 2002; Mulindabigwi 2006). Thereby, 'phases of expansion' are normally followed by 'phases of intensification' (Bohlinger 1998; Igué 2000; Mulindabigwi 2006). Fortunately, intensification also reduces the frequency of bush fires.

I-3.10.3 Morocco

The total agricultural area in Morocco amounts to 9.3 M ha or 21% of the country's total surface. Tree crops comprise 0.9 M ha. Sugar beet, cereals, legumes, and vegetables like tomato and cucurbits are the main rotating crops. Among the tree crops, olive and citrus are highly important, together with other fruit crops like almond, peach, apricot, date, and pistachio. Rainfed agriculture is progressing at a much slower pace for obvious climatic reasons. In the hilly areas, almond and apple are now playing an important role. Irrigated land approaches 1.5 M ha, or 16% of the total cultivated area (see table I-3.10.1). The most important irrigated crops are cereal, fodder, olive, legume, citrus, and sugar beet. Morocco has become a major exporter of horticultural products.

Table I-3.10.1: Irrigated area per basin (Source: FAO 2005).

Catchment basin	in 1000 ha	Available water resources (Mm^3)
Moulouya	155.5	1,844
Loukos & Mediterranean coast	63.6	4,312
Sebou	333.2	5,322
Bouregreg & Atlantic coast	28.3	979
Oum Rbiaâ & Jadida-Safi coast	478.4	4,180
Tensift & Safi-Essaouira coast	132.9	1,188
Souss-Massa & Agadir-Tiznit coast	141.0	1,107
South Atlas	125.2	1,741
Total	1,458.2	20,673

Animal husbandry is a very important sector of the Moroccan agriculture. Sheep, goats, and cattle are part of the Moroccan landscape. In recent years, intensification of animal husbandry has been observed in all irrigation perimeters. Milk production, for example, is now an important output, particularly in combination with sugar beet production. Intensive peri-urban poultry production can be observed throughout the country.

Agriculture has extended from the hilly silvopastoral systems into the Sahara region. Only a very few wadis permit date-palm growing and oasis-style irrigated agriculture as, for example, in the IMPETUS project area of the Drâa basin in Morocco (Finckh and Poete 2008).

I-3.10.4 Agricultural systems as concentrators and dilutors of resources

Agricultural systems throughout Northwest Africa can be differentiated by their efficiency at concentrating necessary resources for agricultural production. Morocco is leading in the harvesting of water resources and in allocating all necessary production inputs into vast irrigation schemes, even into plastic tunnels, thereby reducing fallowing to a minimum. Animal husbandry in the whole of Northwest Africa provides a good example of how to concentrate energy from sparsely covered pastures. South of the Tropic of Cancer, concentration techniques become wasteful of natural resources as can be seen from periodic bush fires. In the IMPETUS project area of the Ouémé basin in Benin, bush fires can run up to three times into the same field during the same year (see subsect. I-7.1.2; Thamm 2008). In the Ouémé basin, the overall rotation is a 2:1 proportion of cropping to fallowing. However, due to demographic pressure, fallow land is on the decrease and with it, soil fertility.

Agriculture dilutes previously concentrated resources across farmlands (Janssens et al. 2009). This dilution process is prone to dissipative energy losses. Countries like Morocco are making great efforts at saving water by better irrigation management, including drip irrigation, laser leveling of irrigated fields, and drainage con-

trol. Morocco has managed to control the major Sebou river and to reduce the flooding of the rich Gharb irrigation perimeter. Hence, diluting irrigation water in the field is likely to allow the water to reach plants more efficiently and to reduce energy dissipation. Toward the drier parts of Northwest Africa, multi-layered oasis-style agriculture offsets some of the evaporative losses.

South of the Tropic of Cancer, there is a real problem of diluted resources across the field. Irrigation is underutilized, and fertilizer application techniques are poorly differentiated as a function of specific soil quality and specific crop. Some cotton-producing countries use just one fertilizer formula for the whole country. Synergistic effects from water-fertilizer-x-pesticide combinations are poor due to inadequate logistics and untimely supply of all three production components. In Benin, tree crops are playing an increasing role, among them cashew and teak. This development process can be seen as a way of better diluting both labor efforts and production inputs while improving the overall environment.

The intensification of agriculture in Northwest Africa results in a direct betterment of food security. Indirectly, the larger importance of agricultural marketing allows for the additional exchange of goods. West Africa is now slowly evolving from using an extensive to a more intensive approach as arable land becomes scarce and as traditional farming is often outcompeted by cheap imports. Because of rising food prices, West African urban populations have difficulty filling their food basket.

I-3.11 Health and water

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Health problems in West Africa differ in various aspects. Public health systems are challenged by diseases related to specific climate factors, but they are also challenged by non-environmentally associated diseases that impact public health, such as HIV infections. Furthermore, the availability of drinking water is essential for human beings, and drinking water quality in terms of chemical, microbiological, and virological parameters influence the state of health in the population. Numerous infectious diseases are spread by drinking water and can cause severe illness in susceptible human beings. The transmission of bacteria, protozoa and viruses can also be spread through different routes, like person-to-person or vector-to-person. Vectors are animals, which acquire infectious germs from humans/animals and transmit the disease to new hosts. Environmental factors directly influence the survival of vectors and thus the likelihood of human diseases, which therefore varies during the course of the year. Whereas in industrial nations, cardiovascular disease and malignant cancer are the main causes of death in adults, in the developing countries of Africa, infectious diseases continue to contribute to relevant mortality rates in children and adults.

I-3.11.1 West Africa

In West Africa, the most prominent vector-borne disease influenced by water availability and temperature is malaria. Malarial infections only occur in areas where infected mosquitoes survive and replicate so that transmission to humans can take place. The likelihood of malaria infection differs in Southwest Africa according to climate factors. In some areas, malaria infections are frequently observed throughout the year. In other areas, malaria only occurs sporadically in seasonal patterns (see sect. II-4.5 for further details). A number of infectious microbes, like malaria, need a vector to infect humans. Viruses causing yellow fever, Rift Valley fever, dengue fever and lassa fever are especially found in West Saharan Africa. Yellow fever infections can take different courses, from mild symptoms to severe illness, the latter of which typically occurs in two phases. Although immunization programs lower the burden of this disease, natural infections in monkeys secure the maintenance of the virus, especially in the rural areas of West Africa. Dengue viruses share the same route of transmission, as well as some clinical symptoms, in

patients infected with the yellow fever virus. However, severe illnesses mainly occur in patients previously infected with one of the other dengue virus types. Before 1970, only nine countries had experienced epidemics of the severe form of the dengue hemorrhagic fever. Today, the expanding geographic distribution of the four dengue viruses and their mosquito vectors has led to epidemics in more than 100 countries, including parts of West Africa. Another virus potentially causing hemorrhagic fever in infected patients is called the lassa virus. Lassa virus is known to be endemic in Guinea, Liberia, Sierra Leone, and parts of Nigeria, and is transmitted by excreta from rodents carrying the virus without symptoms. Only accidental infections and death and abortion in the livestock are reported for the Rift Valley fever virus, which is also transmitted by mosquitoes. The water-flea-transmitted *dracunculiasis* (commonly known as Guinea worm disease) has been considered eradicated in Benin since 2007, while cases are still reported in Ghana, Burkina Faso, Mali, Niger, Nigeria, and Togo (World-Health-Organization 2009). Further infectious diseases with animal reservoirs are West *African trypanosomiasis* (African sleeping sickness), rickettsial diseases, *micro-* and *macrofilariasis*, *cutaneous leishmaniasis*, and *schistosomiasis* (bilharzia). For most of these diseases (except malaria), no reliable statistics are available.

Water-borne infectious diseases in developing countries, especially in areas without general water supply and appropriate disinfection measurements, lead to major public health problems with high mortality rates in susceptible people (small children, immunocompromised patients). In North America, 15-30% of all gastrointestinal diseases are suspected as being water-related (Payment et al. 1997). In contrast, over 88% of diarrheal diseases worldwide are water-borne or water-related (Jiang 2006). Only 37.4% of households have access to piped water sources in Benin, West Africa, and in rural areas even fewer. Infectious agents can be maintained in the environment after being egested in human excrement and can cause diseases in susceptible individuals. A study of infectious agents in stool samples of individuals in Ghana revealed parasites in 95% of the cases including amoeboids, ascaris, eucestoda, and tapeworms. Since the environment determines the survival of microbes outside of a host, changes in the environment might result in decreased or increased environmental exposure rates of humans to infectious microbes. In the environment, viruses are more robust than bacteria, but they lack replication capacity outside of a cell, leading to a continuous degradation over time. Even very small amounts of viruses may be capable of initiating an infection. Depending on temperature, UV-light exposure and other factors, viruses can survive up to two years in aquatic matrices. Despite their ability to maintain over a long period of time in environmental samples, the detection of viruses in water samples is hampered by low virus concentrations. This calls for concentration methods before virus detection can be performed. Due to detection problems, viral water quality is rarely analyzed in detail. However, bacterial indicators seem to be inappropriate for analyzing viral contamination since viruses are often found without any bacterial indicator for fecal contamination (Baggi et al. 2001; Borchardt et al. 2004).

Three groups of viruses transmitted by the fecal-oral route can be distinguished according to the related diseases (gastroenteritis, hepatitis, and other clinical symptoms). Viruses that cause gastroenteritis are especially prone to being transmitted by this route. Several different viruses, like astroviruses, noroviruses, adenoviruses (types 31, 40, 41), and rotaviruses, result in diarrheal diseases in humans. Astroviruses and adenoviruses are found in adults and children, mainly with mild symptoms of diarrhea. Noroviruses are often found in epidemic patterns since not only is the stool infectious, but aerosols from vomiting patients can also transmit the virus. Moreover, immunity to norovirus infections only lasts about six months, so reinfections can often occur. Severe diarrhea, especially in small children and immunocompromised patients, is often caused by rotaviruses. The fatal outcome of infant diarrhea substantially contributes to the high mortality rate of children under the age of five in developing countries (Cunliffe et al. 2002). In Benin, the probability of dying under 5 years (under-5 mortality rate) was 152 per 1,000 live births in 2004, and 17.1% of the deaths were caused by diarrheal diseases (World-Health-Organization 2009). Two hepatitis viruses (Hepatitis-A- and hepatitis-E-viruses) are also transmitted by the fecal-oral route. These cause an acute hepatitis in infected patients rarely associated with complications like fulminant hepatitis. Due to an incubation period of one to two months for both viruses, with often only mild symptoms, it is difficult to trace epidemics back to their origin. Clinical patterns of infections with enteroviruses, adenoviruses, and polioviruses largely vary from myocarditis to meningitis, encephalitis, respiratory disease, and keratoconjunctivitis. These viruses are commonly found in stool samples from patients but are also found in the course of clinically inapparent infections. The heterogeneous clinical manifestation, as well as the low manifestation index, hampers the analysis of these infections as water-related or transmitted diseases. Although poliovirus infections related to water have been discussed several times, the clinical impact has remained unclear. Since Benin is located next to Nigeria, one of four countries that still have ongoing endemic Poliovirus infections, the potential risk of an increase in the disease burden can be anticipated.

Pathogens can reach drinking water sources by different pathways. Poor design or construction of water wells can lead to a rapid bypass mechanism, further boosted by water flows in the soil. This is called a localized pathway. On the other hand, transport of viruses through the subsoil to the water table can result in the contamination of drinking water sources. This is called the aquifer pathway (Godfrey et al. 2005). During the wet season, water flow in the upper soil can ease virus transport by localized pathways (Rohayem et al. 2002; Jiang et al. 2007). During the dry season, contamination of drinking water sources can occur because of aquifer pathways in the ground flow. It is even speculated that viruses can travel distances greater than 1,000 m under optimized conditions (Robertson et al. 1997).

I-3.11.2 Northwest Africa

In Morocco, vector-borne diseases are less prominent than in West Africa. Malaria infections, especially, are only rarely observed. Nevertheless, *leishmanisiasis* and dengue virus infections have been reported. In contrast to sub-Saharan Africa, *borrelia burgdorferi*, West Nile fever and *phlebotomus* fever infections have been observed. West Nile fever, typically found in northern Africa, is now also prevalent in northern America. The course of dieses is generally mild, but severe complications have been described. *Phlebotomus* viruses are found throughout the Mediterranean region and can cause normally self-limiting diseases of the meninges.

Water availability and water quality are of similar importance as in Benin. The previously discussed bacteria and viruses are also responsible for water-borne infections in this geographic region. Problems for public health systems from improper water supplies are a major obstacle in achieving sustained improvement of living conditions in developing areas of the world.

I-3.12 References for chapter I-3

Affaton P, Rahaman MA, Trompette R, Souhy Y (1991) The Dahomeyide Orogen: Tectonothermal evolution and relationships with the Volta Basin. In: Dallemeyer RD, Lérorché JP (eds) The West African Orogens and Circum-Atlantic Correlatives, pp. 107-122. Springer, Berlin, Heidelberg, New York

Akapi JA (2002) Ackerbauern und mobile Tierhalter in Zentral- und Nordbenin. Landnutzungskonflikte und Landesentwicklung. In: Braun G, Freitag U, Kluczka G, Lenz K, Scharfe W, Scholz F (eds) Abhandlungen – Anthropogeographie 63. Institut für Geographische Wissenschaften. Freie Universität Berlin, Berlin

Arboleya M-L, Babault J, Owen LA, Teixell A, Finkel RC (2008) Timing and nature of Quaternary fluvial incision in the Ouarzazate foreland basin, Morocco. J Geol Soc London 165:1059-1073

Baggi F, Demarta A, Peduzzi R (2001) Persistence of viral pathogens and bacteriophages during sewage treatment: lack of correlation with indicator bacteria. Res Microbiol 152:743-51

Beauchamp W, Allmendinger RW, Barazangi M, Demnati A, El Alji M, Dahmani M (1999) Inversion tectonics and the evolution of the High Atlas Mountains (Morocco), based on a geological-geophysical transect. Tectonics 18(2):163-184

Bellion YJ-C (1987) Histoire geódynamique post-paleozoique de l'Afrique de l'ouest d'après l'étude de quelques bassins sédimentaires (Sénégal, Taoudenni, Iullemmeden, Tchad). University of Avignon, CIFEG, Paris

Benassi M (2008) Évolution du champ pluviométrique au Maroc. Direction de la Météorologie Nationale, Casablanca

Bohlinger B (1998) Die Spontane Vegetation in traditionellen Anbausystemen Benins: Ihre Bedeutung und Möglichkeiten des Managements. PLITS 16 (1). University of Hohenheim, Stuttgart

Borchardt MA, Haas NL, Hunt RJ (2004) Vulnerability of drinking-water wells in La Crosse, Wisconsin, to enteric-virus contamination from surface water contributions. Appl Environ Microb 70:5937-46

Born K, Piecha K, Fink A (2008a) Shifting climate zones in the northwestern Maghreb. In: Schulz O, Judex M (eds.) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 13–14. Department of Geography, University of Bonn, Bonn

Born K, Fink A, Paeth H (2008b) Dry and Wet Periods in the Northwestern Maghreb for Present Day and Future Climate Conditions. Meteorol Z 17:533-551

Bouidida A (1990) Salinité des eaux de la vallee du Drâa - situation actuelle et evolution. Institut Agronomique et Veterinaire. Diploma thesis, University Hassan II, Rabat

Brancic B (1968) Sols de la palmeraie de Fezzouata. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. Ouarzazate, ORMVAO

Burkhard M, Cartig S, Helg U, Robert-Charrue C, Soulaimani A (2006) Tectonics of the Anti-Atlas. C R Geosci 338:11-24

Cappy S (2006) Hydrogeological characterization of the Upper Drâa Catchment, Morocco. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2007/cappy_sebastien/.
Accessed 12 November 2009

Cavallar W (1950) Esquisse Préliminaire de la Carte des Sols du Maroc, Direction de l'Agriculture, cu Commerce et des Forêts du Maroc. Division de l'Agriculture et de l'Elevage: N40°0-N31°30;W16°0-W2°0.
http://eusoils.jrc.ec.europa.eu/esdb_archive/EuDASM/Africa/maps/afr_masoil.htm.
Accessed 12 November 2009

CENATEL (2002) Rapport final: Base de données georeferencées sur l'utilisation agricole des terres au Bénin. Contrat N° 23428. Cotonou

Choubert G, Faure-Muret A (1983) Anti Atlas. In: Bertrand J-M, Fabre J (eds) Afrique de l'ouest, pp. 80-95. Pergamon Press, Oxford
CIA (2009a) CIA World Factbook. https://www.cia.gov/library/publications/the-world-factbook/-rankorder/2003rank.html. Accessed 12 November 2009
CIA (2009b) CIA World Factbook. https://www.cia.gov/library/publications/the-world-factbook/-geos/bn.html. Accessed 20 November 2009
Collins AS, Pisarevsky SA (2005) Amalgamating eastern Gondwana: The evolution of the Circum-Indian Orogens. Earth Sci Rev 71:229-270
Cunliffe NA, Bresee JS, Hart CA (2002) Rotavirus vaccines: development, current issues and future prospects. J Infection 45:1-9
Davidson Basil (1995) Africa in History. Simon & Schuster, New York
Direction de la Statistique (1995) Population Légale du Royaume d'après le Recensement Général de la Population et de l'Habitat (Septembre 1994) (RGPH 1994). Rabat
Dixon JA, Gibbon DP, Gulliver A (2001) Farming systems and poverty: improving farmers' livelihoods in a changing world, Training Materials for Agricultural Planning, Food and Agriculture Organization of the United Nations. World Bank, FAO, Rome
Doevenspeck M (2005) Migration im ländlichen Benin. Sozialgeographische Untersuchungen an einer afrikanischen Frontier. Verlag für Entwicklungspolitik, Saarbrücken
El-Fahem T (2008) Hydrogeological conceptualisation of a tropical river catchment in a crystalline basement area and transfer into a numerical groundwater flow model - Case study for the Upper Ouémé catchment in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/el-fahem_tobias. Accessed 12 November 2009
Ennih N, Liégeois J-P (2008) The boundaries of the West African Craton, with spatial reference to the basement of the Moroccan metacratonic Anti Atlas belt, In: Ennih N, Liégeois J-P (eds) The boundaries of the West African Craton, Geol Soc Spec Publ. doi:10.1144/SP297.1
FAO (2005) AQUASTAT country profiles. FAO, Rome. http://www.fao.org/ag/agl/aglw/AQUASTAT/countries/index.stm. Accessed 2 October 2009
FAO AQUASTAT (2009) FAO's Information System on Water and Agriculture. http://www.fao.org/nr/water/aquastat/dbases/index.stm. Accessed 20 November 2009
FAO/AGL (2003) WRB Map of World Soil Resources. http://www.fao.org/ag/agl/agll/wrb/soilres.stm. Accessed 12 November 2009
Fass T (2004) Hydrogeologie im Aguima Einzugsgebiet in Benin/Westafrika. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/fass_thorsten. Accessed 12 November 2009
Faure P, Volkoff B (1998) Some factors affecting regional differentiation of the soils in the Republic of Benin (West Africa). Catena 32:281-306
Fennane M (2004) Propositions de zones importantes pour les plantes au Maroc (ZIP Maroc). http://www.uicnmed.org/web2007/documentos/zip_rapport_atelier_rabat.pdf. Accessed 12 January 2010
Fink AH (2006) Das westafrikanische Monsunsystem (The West African monsoon system). Promet 32:114–122
Fink AH, Kotthaus S, Pohle S (2008b) Rainfall Variability in West Africa. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 21-22. Department of Geography, University of Bonn, Bonn
Fink AH, Piecha K, Brücher T, Knippertz P (2008a) Precipitation Variability in Northwest Africa. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 11-12. Department of Geography, University of Bonn, Bonn
Fraedrich K, Gerstengarbe FW, Werner PC (2001) Climate shift during the last century. Climatic Change 50:405-417

Gaba E (2008) Map of the African Continent. Lambert azimutal equal-area projection, WGS84 datum, standard meridian: 15°E, standard parallel: 0°, Scale: 1:15,000,000 (accuracy: 3,75 km). http://upload.wikimedia.org/wikipedia/commons/thumb/9/95/African_continent-fr.svg/635px-African_continent-fr.svg.png. Accessed 20 November 2009

Gebhardt H, Glaser R, Radtke U, Reuber P (eds) (2007) Geographie - Physische Geographie und Humangeographie. Elsevier, Spektrum Akademischer Verlag, Heidelberg

Giertz S, Steup G, Sintondji L, Gbaguidi F, Schönbrodt S (2008) Survey of Inland Valleys in the Upper Ouémé Catchment. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 99-100. Department of Geography, University of Bonn, Bonn

Giertz S, Schönbrodt S (2008) Geomorphology of Benin. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 63-64. Department of Geography, University of Bonn, Bonn

Godfrey S, Timo F, Smith M (2005) Relationship between rainfall and microbiological contamination of shallow groundwater in Northern Mozambique. Water SA 31:609-614

Goetze D, Hörsch B, Porembski S (2006) Dynamics of forest-savanna mosaics in north-eastern Ivory Coast from 1954 to 2002. J Biogeogr 33:653-664

Griffiths JF (1972) The Mediterranean zone. In: Landsberg HE (ed) Chapter 2 of „World Survey of Climatology“, pp. 37-74. Elsevier, Amsterdam

Griffiths JF, Soliman KH (1972) The northern desert (Sahara). In: Landsberg HE (ed) Chapter 3 of „World Survey of Climatology“, pp. 75-131. Elsevier, Amsterdam

Guillaumet JL, Adjanohoun E (1971) La végétation de la Côte d'Ivoire. In: Avenard JM, Eldin E, Girard G, Sircoulon J, Touchebeuf P, Guillaumet JL, Adjanohoun E, Perraud A (eds) Le milieu naturel de la Côte d'Ivoire, pp. 157-263. ORSTOM, Paris

Hadjer K (2006) Geschlecht, Magie und Geld. Sozial eingebettete und okkulte Ökonomien in Benin, Westafrika. Doctoral thesis, University of Cologne, Cologne

Hadjer K (2008) Occultism and its Impacts on economic behaviour. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 119-120. Department of Geography, University of Bonn, Bonn

Haut Commissariat au Plan (HCP) (2009) Horloge de la population. http://www.hcp.ma/Horloge.aspx. Accessed 12 November 2009

Haut Commissariat au Plan (HCP) (2007) Les Indicateurs Sociaux du Maroc en 2007. Rabat

Heinitz W, Buchelt M, Jacobshagen V (1986) Early diagenetic tectonic structures in the sedimentary cover of the central Anti-Atlas (South Morocco). N Jb Geol Paläont Mh 6:342-357

Hettner A (1935) Vergleichende Länderkunde. 4. Vol. 1933-1935. Teubner, Leipzig

Igué AM (2000) The use of a soil and terrain database for land evaluation procedures: Case study of Central Benin. Hohenheimer Bodenkundliche Hefte 58. University of Hohenheim. Stuttgart

Igué AM, Gaiser T, Stahr K (2004) A soil and terrain digital database for improved land use planning in Central Benin. Eur J Agron 21:41-52

IMF (2005) IMF Country Report Morocco No. 05/420 - Statistical Appendix. Washington DC

IMF (2008) IMF Country Report Benin No. 08/287 - Statistical Appendix. Washington DC

Index Mundi (2008) Benin Imports – Commodities. http://www.indexmundi.com/benin/imports_commodities.html. Accessed 12 November 2009

Institut National de la Statistique et de l'Analyse Economique INSAE (2003) Troisième Recensement Général de la Population et de l'Habitation. Internal governmental data set. Cotonou

Ismat Z (2008) Folding and kinematics expressed in fracture patterns: An example from the Anti-Atlas fold belt, Morocco. J Struct Geol 30:1396-1404

Janssens MJJ, Pohlan J, Keutgen N, Torrico JC (2009) Plants are not weight watchers but space invaders. In: Technology, Resource Management & Development Volume No. 6 – Special issue in Honor of Prof. Dr. Hartmut Gaese. Technology and Resource Management in the Tropics and Subtropics – State of the Art and Future Prospects, pp. 115-122. Fachhochschule Köln, Institute for Technology and Resources in the Tropics and Subtropics, Cologne

Jiang SC (2006) Human adenoviruses in water: occurrence and health implications: a critical review. Environ Sci Technol 40:7132-40
Jiang SC, Chu W, He JW (2007) Seasonal detection of human viruses and coliphage in Newport Bay, California. Appl Environ Microb 73:6468-74
Jongkind CCH (2004) Checklist of Upper Guinea forest species. In: Poorter L, Bongers F, Kouamé FN, Hawthorne WD (eds) Biodiversity of West African forests: an ecological atlas of woody plant species, pp. 447-477. CABI Publishing, Wallingford
Jossen JA, Filali MJ (1988) Bassin de Ouarzazate – Synthese stratigraphique et structurale. Projet PNUD-DRPE MOR/86/004, Exploration des eaux profondes, Contribution à l'étude des aquifères profonds, Direction de la recherche et de la planification de l'eau. Rabat
Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., Department of Geography, University of Bonn, Bonn
Junge B (2004) Die Böden des oberen Ouémé-Einzuggebietes in Benin/Westafrika: Pedologie, Klassifizierung, Nutzung und Degradierung. Doctoral thesis, University of Bonn, Bonn
Junge B (2004) Die Böden im oberen Ouémé-Einzugsgebiet: Pedogenese, Klassifikation, Nutzung und Degradierung. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2004/junge_birte/index.htm. Accessed 12 November 2009
Jurion F, Henry J (1967) De l'Agriculture Itinérante à l'Agriculture Intensifiée. Publications de l'Institut National pour l'Etude Agronomique du Congo (INEAC), Brussels
Klose S, Reichert B, Lahmouri A (2008) Management options for a sustainable groundwater use in the Middle Drâa Oases under the pressure of climatic changes. In: Zereini F, Hötzl H (eds) Climatic Changes and Water Resources in the Middle East and North Africa, pp. 179-195. Springer, Berlin
Knippertz P, Christoph M, Speth P (2003) Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorol Atmos Phys 83:67-88
Lebel T, Ali A (2009) Recent trends in the Central and Western Sahel rainfall regime (1990-2007). J Hydrol 375:52-64
Linjouom M (2007) The Impact of the Real Exchange rate on Manufacturing Exports in Benin. Africa Region Working Paper Series No. 107, World Bank, Washington D.C.
Lloeje NP (1972) A New Geography of West Africa, 2nd edn. Longman Group, Hong Kong
Maley J (2001) The impact of arid phases on the African rain forest through geological history. In: Weber W, White LJT, Vedder A, Naughton-Treves L (eds) African rain forest ecology and conservation: an interdisciplinary perspective, pp. 68-87. Yale University Press, New Haven
McCullough JJ (2003) Colonial Africa Graphic. http://upload.wikimedia.org/wikipedia/commons/0/02/Colafrica.jpg. Accessed 20 November 2009
McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. Preprints, 8th Conference on Applied Climatology, Jan. 17-22, Anaheim, CA
Mensching H (1957) Marokko – Die Landschaften im Maghreb. Keysersche Verlagsbuchhandlung, Heidelberg
Michard A (1976) Eléments de géologie marocaine. Notes et mémoires du Service Géologique No. 252, Direction des Mines, de la Géologie et de l'Energie. Rabat
Michard A, Saddiqi O, Chalouan A, Frizon de Lamotte D (eds) (2008) Continental Evolution: The geology of Morocco – Structure, Stratigraphy and Tectonics of the African-Atlantic-Mediterranean Triple Junction. Springer, Berlin
Morgan WB, Pugh JC (1969) West Africa. Butler & Tanner, London
Mulindabigwi V (2006) Influence des systèmes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin. Doctoral thesis, University of Bonn, Bonn
Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853-858

Natta AK, Porembski S (2003) Ouémé and Comoé: forest-savanna border relationships in two riparian ecosystems in West Africa. Bot Jahrb Syst 124:383-396

Nelson A (2004) African Population Database. UNEP GRID, Sioux Falls. http://na.unep.net/unepdownload/form.php?type=africa. Accessed 12 November 2009

Neumann K, Hahn-Hadjali K, Salzmann U (2004) Die Savanne der Sudanzone in Westafrika: Natürlich oder menschengemacht. In: Albert K-D, Löhr D, Neumann K (eds) Mensch und Natur in Westafrika: Kapitel. 2.1. Ergebnisse aus dem Sonderforschungsbereich 268 „Kulturentwicklung und Sprachgeschichte im Naturraum Westafrikanische Savanne, pp. 39-68. DFG. Wiley-VCH Verlag, Weinheim

OECD (2007) African Economic Outlook. Paris

Payment P, Berte A, and Fleury C (1997) Sources of variation in isolation rate of Giardia lamblia cysts and their homogeneous distribution in river water entering a water treatment plant. Can J Microbiol 43:687-9

Piqué A (2001) Geology of Northwest Africa. Gebr. Borntraeger, Berlin

Porembski S (2000) West African inselberg vegetation. In: Porembski S, Barthlott W (eds) Inselbergs: biotic diversity of isolated rock outcrops in tropical and temperate regions, pp 177-211. Springer, Berlin, Heidelberg, New York

Quézel P (1957) Peuplement végétal des hautes montagnes de l'Afrique du Nord. Lechevalier, Paris

Radanovic R (1968a) Sols de la palmeraie de Tinzouline. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Radanovic R (1968b) Sols de la palmeraie de Ternata. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Radanovic R (1968c) Sols de la palmeraie de Mezguita. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Raemaekers R (ed) (2001) Crop Production in Tropical Africa. DGIC, Directorate General for International Cooperation, Brussels

Robertson JB, Edberg SC (1997) Natural protection of spring and well drinking water against surface microbial contamination. I. Hydrogeological parameters. Crit Rev Microbiol 23:143-78

Rohayem J, Dumke R, Jaeger K, Schroter-Bobsin U, Mogel M, Kruse A, Jacobs E, Rethwilm A (2006) Assessing the risk of transmission of viral diseases in flooded areas: viral load of the River Elbe in Dresden during the flood of August 2002. Intervirology 49:370-6

Röhrig J (2008) Evaluation of agricultural land resources in Benin by regionalisation of the marginality index using satellite data. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/roehrig_julia. Accesssed 12 September 2009

Röhrig J, Laudien R (2009) Evaluation of agricultural land resources by implementing a computer-based spatial decision support system for national deciders in Benin, West Africa. J Appl Remote Sens. doi:10.1117/1.3079033

Salzmann U (2000) Are modern savannas degraded forests? - A Holocene pollen record from the Sudanian vegetation zone of NE Nigeria. Veg Hist Archaeobot 9:1-15

Sarukhán J, Whyte A (eds) (2005) Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Desertification Synthesis. World Resources Institute, Washington DC

Schulz O (2008) Snow cover variability in the High Atlas Mountains. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 53-54. Department of Geography, University of Bonn, Bonn

Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn. Department of Geography, University of Bonn, Bonn

Shanin M (2002) Hydrology and water resources of Africa. Water Science and Technology Library. Kluwer Academic Publisher

Stets J, Wurster O (1981) Zur Strukturgeschichte des Hohen Atlas in Marokko. Geol Rundsch 70(2):801-841

Taylor G, Eggleton RA (2001) Regolith Geology and Geomorphology. John Wiley & Sons, Chichester

The Worldbank Group (2008a) Nigeria Data Profile. http://devdata.worldbank.org/external/CPProfile.asp?PTYPE=CP&CCODE=NGA. Accessed 12 November 2009

The Worldbank Group (2008b) Sub-Sahran-Africa Data Profile, http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20535285~menuPK:1192694~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html. Accessed 12 November 2009

World Bank (2008) Country Brief Benin. Update September 2008, Washington DC

Tidjani E-H, Affaton P, Louis P, Socohou A (1997) Gravity characteristics of the Pan-African Orogen in Ghana, Togo and Benin (west Africa). J Afr Earth Sci 24(3):241-258

UNDP (2007, 2008) Human Development Report. Brasilia

United Nations Development Programme UNDP (2009) Human Development Indices: A statistical update 2008 - HDI rankings. http://hdr.undp.org/en/statistics/. Accessed 12 November 2009

United Nations Statistical Yearbook (2008) Fifty-second issue, New York

United Nations UN (2007) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Urbanization Prospects: The 2007 Revision Population Database. http://esa.un.org/unup/. Accessed 12 November 2009

United Nations UN (2008) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2008 Revision, http://esa.un.org/unpp. Accessed 12 November 2009

Van Engelen V (1993) Global and national soils and terrain digital databases (SOTER). Procedures manual. ISRIC, Wageningen

Van-Chi-Bonnardel R (ed) (1996) L'Atlas Jeune Afrique du Continent Africain. Editions Jaguar, Paris

Vollmert P, Fink AH, Besler H (2004) Ghana- and Dahomey-Trockenzone: Ursachen für eine Niederschlagsanomalie im tropischen Westafrika (in German). Erde 134:375-393

Weller U (2002) Land evaluation and land use planning for Southern Benin (West Africa) BENSOTER. Hohenheimer Bodenkundliche Hefte 67. Institut für Bodenkunde und Standortlehre. University of Hohenheim. Stuttgart

Wezel A, Böcker R (2000) Vegetation of Benin. In: Graef F, Lawrence IM, von Oppen M (eds) Adapted Farming in West Africa: Issues, potentials and perspectives, pp. 219-226. Verlag Ulrich E. Grauer, Stuttgart

White F (1983) The vegetation of Africa. A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa. UNESCO, Paris

Wiese B (1997) Afrika. Ressourcen, Wirtschaft, Entwicklung. Teubner, Stuttgart

World-Health-Organisation (2009) http://www.who.int/mediacentre/factsheets/en/. Accessed 12 November 2009

World Bank (2007) World Development Indicators. Washington DC

World Bank (2008) Country Brief Benin. Update September 2008, Washington DC

Wright EP, Burgess W (1992) The hydrogeology of crystalline basement in Africa. Geol Soc Spec Pap 66:264





4 Measurement concepts

4.1 Hydro-meteorological measurements in Benin

4.1.1 Introduction

4.1.2 Meteorological measurements

4.1.3 Hydrological measurements

4.2 Weather and climate monitoring in Benin

4.2.1 Introduction

4.2.2 Meteorological observations in Benin used for data products

4.2.3 Data products and monitoring

4.3 Hydro-meteorological measurements in the Drâa catchment

4.3.1 Introduction

4.3.2 Meteorological measurements at the test sites

4.3.3 Hydrological and other measurements

I-4 Measurement concepts

A. H. Fink

Keywords: Measurement concepts, Haute Vallée de l'Ouémé, Drâa catchment, IMPETUS geonetwork, AMMA data base

As discussed in chapter I-3, the climatic, ecological, and hydrologic environments in the Ouémé and Drâa catchments are very different. A scarcity of hydro-meteorological and vegetation data is common to both regions and is typical for many African catchments, both for spatial density of measurement stations and for long-term homogeneous time series. These data are necessary for process studies, trend analyses, as well as for model initialization and validation. The measurement concepts developed within IMPETUS incorporated these challenges and provided a database for knowledge-based adaptations to a changing environment.

The climate and vegetation gradients in the Ouémé catchment are smooth, and ecological units are not nearly as diverse as those found in the second IMPETUS study region in the High Atlas Mountains. Additionally, a hydro-meteorological network was established in 1997 by the French IRD-CATCH project (*Institute pour le Développement-Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique*) in the ecologically homogeneous *Haute Vallée de l'Ouémé* (HVO). The spatio-temporal variability of rainfall is very large in the Ouémé catchment, which is typical for humid tropical climates. Given financial and logistical constraints, the placement of nine IMPETUS rain gauges and four weather stations was therefore intended to complement the French network in order to make better studies of propagating rainfall systems and better assessments of water balance in the HVO (see sect. I-4.1). To achieve these goals, rainfall estimates were complemented by high-resolution gridded rainfall data inferred from gauge-calibrated satellite radiation measurements (see sect. I-4.2). Satellite-based gridded estimates of global radiation, temperature, relative humidity, and evaporation were also compiled. The surface stations were mostly deployed in the vicinity of the IMPETUS super site at the Aguima catchment in the southwestern part of the HVO. The intense gauging of this small 30 km² catchment was done to upscale the key hydrological processes identified in this small catchment to the HVO and also to the entire Ouémé catchment.

In the Drâa catchment, a series of thirteen weather stations was deployed along the climate, hygric, and vegetation gradients, ranging from the Saharan foothills of the Antiatlas Mountains to the summit level of the High Atlas Mountains, where snow depth and the water equivalent of the snow pack were monitored (see sect. I-4.3). Vegetation test sites were attached to the meteorological enclosures, including fenced exclosures, in order to monitor the climate-dependent vegetation development with and without grazing. The variability in geologic settings and land use

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were also considered before the sites were chosen. This network was complemented by some water level recorders, primarily in higher parts of the High Atlas Mountains. The IMPETUS station transect in Morocco is unique because it covers the entire ecological gradient, which is typically found at the Saharan side of the Atlas Mountains.

GLOWA-IMPETUS data for both catchments is on the IMPETUS geonetwork web portal, available at http://geonetwork.impetus.uni-koeln.de. The Benin data is mirrored at the AMMA[1] database, available at http://amma-international.org/database. The AMMA site probably contains the largest collection of geophysical data for tropical West Africa.

[1] The IRD-CATCH project was renamed IRD-CATCH/AMMA (African Monsoon Multidisciplinary Analyses) in the year of 2005.

I-4.1 Hydro-meteorological measurements in Benin

S. Pohle, A. H. Fink, S. Giertz, and B. Diekkrüger

Abstract

Hydro-meteorological measurement concepts for the semi-humid tropical climate of the Ouémé catchment are described. Meteorological stations have been deployed for multiple reasons: (a) to improve assessments of the water balance in the Upper Ouémé catchment; (b) to study precipitating weather systems; and (c) to understand high-impact weather systems. In hydrology, a 'super-site' concept has been applied. The small (30 km^2) Aguima catchment is gauged intensively in order to identify key hydrological processes that must be considered in hydrological models for the entire Ouémé catchment.

Keywords: Aerosols, Aguima super site, anemometer, automatic weather station, flux station, latent heat flux, pyranometer, pyrgeometer, radiation, radiometer, radiosonde, rain gauges, Haute Vallée de l'Ouémé, sensible heat flux, soil heat flux, Soudanian zone, surface energy balance, TDR probes, tensiometer, water level gauge, water level recorder

I-4.1.1 Introduction

Although the scarcity of (digital) hydro-meteorological measurements is a problem in Benin, the country's meteorological and hydrological services have maintained a comparably well-functioning network over recent decades. As mentioned in the preface, the French IRD-CATCH project installed a hydro-meteorological network in the *Haute Vallée de l' Ouémé* (HVO) and launched a substantial initiative to digitize the datasets of the *Direction de la Météorologique Nationale* (DMN) and the *Direction Générale de l'Eau* (DGEau). Thus, the availability of digital hydro-meteorological datasets in Benin was relatively good when the IMPETUS project started in 2000. In addition to the overall measurement concepts outlined in the preface, some amendments to the network of the DMN Benin and Niger that also included two stations outside the HVO were necessary in order to investigate the climatology and nature of high-impact weather systems (e.g., rainfall and associated damaging wind gusts, dust storms). The amendments and the use of the station data in GLOWA-IMPETUS are described in the following sections.

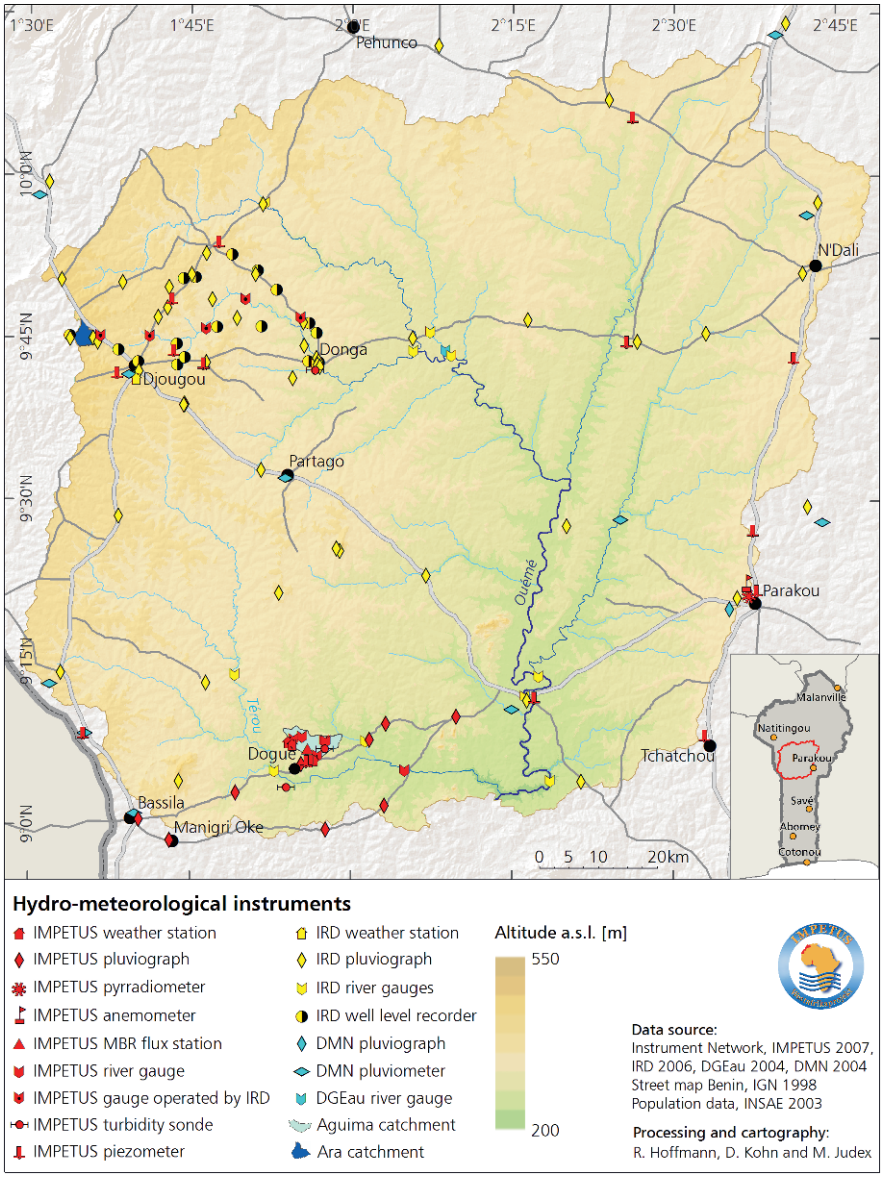

Fig. I-4.1.1: Network of hydro-meteorological instruments in the Upper Ouémé catchment (HVO), Benin. Note the small catchments of the Aguima near Doguè (light blue) and the Ara (dark blue) (Source: Fink and Giertz 2008, amended).

I-4.1.2 Meteorological measurements

Rainfall is one of the most important meteorological variables in tropical West Africa. Rainfall in the tropics is convective in nature (see sect. I-5.1) and is thus rather unevenly distributed over time and space. A high spatial density of rain gauges is indispensible to assess catchment-averaged rainfall amounts. Moreover, high resolution rainfall intensity estimates are pivotal when studying erosion processes or the dynamics of the rainfall systems. Between 1997 and 2006, 65 pluviographs were installed by the GLOWA-IMPETUS and IRD-CATCH/AMMA ("*Institute pour le Développement-Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique/African Monsoon Multidisciplinary Analyses*") projects in the HVO, covering an area of about 15,000 km^2. GLOWA-IMPETUS contributed 13 recording rain gauges that were mostly installed near the Aguima super-site, in the southwestern corner of the HVO (see fig. I-4.1.1). These rain gauges measure precipitation based on the weighing principle and record rainfall intensity at a resolution of up to 0.1 mm min^{-1}. The IRD-CATCH/AMMA rain gauges were clustered in the Donga catchment in the northwestern corner of the HVO (see fig. I-4.1.1). The majority of the CATCH/AMMA rain gauges are of the tipping bucket type, with a resolution of 0.5 mm. A meaningful time resolution to determine rainfall intensity for all gauge types is 5–6 minutes (Fink et al. 2006). Furthermore, 11 pluviometers run by the DMN are read manually every morning. The dense rain gauge network is unique in the sub-humid West African tropics, enabling the study of major rain-bearing weather-systems in the Soudanian zone (Fink et al. 2006; Schrage and Fink 2007).

Three GLOWA-IMPETUS Automatic Weather Stations (AWS) were installed at the Aguima super site near the village of Doguè (see fig. I-4.1.1). These stations provided air temperature, relative humidity, wind, rainfall, radiation, air pressure and soil temperature data. The stations are representative for micro-climatic conditions at forest or agricultural sites, and station descriptions are given in Giertz (2004) and Giertz and Steup (2008). Another AWS was erected by IRD-CATCH/AMMA at the DMN climate station in Djougou (see fig. I-4.1.1) in order to replace the old instruments. The data from this AWS are representative of meteorological stations per regulations set forth by the World Meteorological Organization (WMO). The meteorological network in the HVO was amended in 2004 by a GLOWA-IMPETUS energy flux station at the Aguima super site (see fig. I-4.1.1). It measures wind at a high frequency, radiation, temperature profiles, humidity profiles, soil heat fluxes, soil water potential, air pressure and precipitation. The station is a so-called Modified Bowen Ratio (MBR) flux station after Liu and Foken (2001). While the direct measurement of the sensible heat flux was possible by the use of the ultrasonic anemometer, the determination of the latent heat flux by the MBR approach was inaccurate due to the limited height of the flux tower. In an alternative approach, the latent flux was determined as the residual of the surface energy balance equation, assuming zero heat storage in the soil. The

MBR station provided, with some gaps, the energy balance terms for an agro-meteorological site in central Benin for the period 2004–2009.

In order to observe and investigate wind regimes affecting Benin and to renew the instrumentation at DMN Benin and DMN Niger synoptic stations, GLOWA-IMPETUS installed two wind measurement systems at Parakou (see fig. I-4.1.1; 09.35°N, 2.62°E; Benin) and at Gaya (11.88°N, 3.45°E; Niger) in 2002. These stations ran more or less continuously in collaboration with two African meteorological services until the time of this writing. The system contains an anemometer to measure wind velocity and a wind vane to measure wind direction. The archived data are 10–minute arithmetic means, calculated from measurements at each second. The maximum wind speed during every archived 10–minute interval is also stored. Both stations have been reporting these wind observations to the worldwide WMO Global Telecommunication System (GTS).

Prior to this study, data of long-term net radiation measurements in tropical West Africa were barely available. Therefore, GLOWA-IMPETUS installed two radiometers at meteorological stations in Cotonou (6.35°N, 2.38°E; South Benin) and Parakou (see fig. I-4.1.1) in 2002. The Cotonou station was abandoned in 2009, and the Parakou station is still active. The radiometer measured the incoming and reflected solar radiation with an upward- and downward-facing pyranometer, respectively. Similarly, the incoming and outgoing longwave radiation were recorded with two pyrgeometers. Thus, among other derived parameters, net radiation was determined at a resolution of 10 minutes. The data has been used by Knippertz and Fink (2006) to illustrate multi-day reduction in incoming solar radiation following a major dust storm that crossed the Guinea Coast during early March of 2004. One of the most common applications of the radiometer is to measure net (total) radiation at the earth's surface. Figure I-4.1.2 shows the time series of the 11–day running mean 24–hour net radiation at Cotonou and Parakou for 2007. Parakou exhibits a larger reduction in solar irradiation during the Harmattan season than Cotonou. This reduction is an effect of the lower solar azimuth, but it also reflects a stronger aerosol loading of the atmosphere due to Saha-

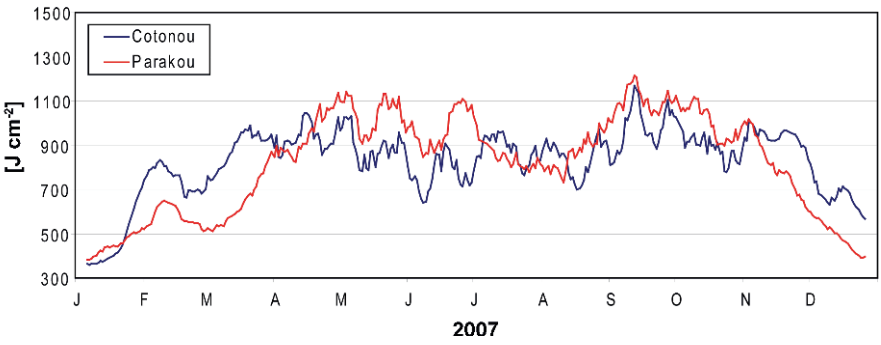

Fig. I-4.1.2: Time series of the 11-day running mean 24-hour net radiation [J cm^{-2}] at Cotonou (blue) and Parakou (red).

ran dust and particles from biomass burning. On the other hand, clear days during pre- and post-monsoon seasons at Parakou frequently exhibit more incoming radiation than at Cotonou. The lower solar irradiation at the latter station may be related to the air pollution and sea spray aerosol content at Cotonou.

Finally, upper-air sounding campaigns took place at Parakou during 2002 and between 2005 and 2008. The 2002 campaign was carried out by GLOWA-IMPETUS and the 2005-2008 campaign was carried out by the European Union-funded AMMA project. However, GLOWA-IMPETUS supported the AMMA campaign. Altogether, about 360 sondes were launched between April and October 2002, and about 1350 sondes were launched between December 2005 and November 2008. From these campaigns, temperature, humidity, wind and pressure profiles at 5 m–10 m vertical resolution are available for different standard times of the day. For the 2002 campaign, radiosonde data was used by Fink et al. (2006), Schrage et al. (2006a), Schrage et al. (2006b), and Schrage and Fink (2007). The AMMA radiosonde campaign is described in Parker et al. (2008).

I-4.1.3 Hydrological measurements

The hydrological network consists of water level gauges, multi-parameter probes (conductivity, turbidity, and temperature), groundwater level measurements, and soil water measurements. In addition to water level measurements of the DGEau at Ouémé-Beterou and Térou-Wanou, 18 water level gauges have been installed since 1997 by the IRD-CATCH/AMMA project in the HVO in the Ouémé, Térou, and Donga rivers and their tributaries (see fig. I-4.1.1). At all gauging stations, discharge measurements are performed regularly by the IRD-CATCH/AMMA project and the DGEau to calculate the stage-discharge relationship. Discharge data has been available since 1950 for the DGEau stations and available since 1997 for the IRD-CATCH/AMMA gauges.

In order to analyze runoff generation processes and sediment yield, the IMPETUS project installed three multi-parameter probes in 2003. During the same year, 12 divers were installed in the HVO to monitor groundwater level fluctuations, 10 of which are currently recording water levels (including a new diver installed in late 2007). Furthermore, 16 water level recorders run by the CATCH project are located in the catchment (Fink and Giertz 2008).

On a local scale, the Ara catchment (13 km²) in the northwest HVO and the Aguima catchment (30 km²) (see fig. I-4.1.1) in southern HVO were equipped with hydrological measuring instruments in order to analyze the hydrological processes. In the Ara catchment, IRD installed a water level gauge, TDR-probes and piezometers. In the Aguima catchment, a dense hydrologic measuring network was established by GLOWA-IMPETUS that included five water level gauges. At these gauges, discharge measurements were carried out during several campaigns in order to calculate the stage-discharge relationship. In order to quantify the dis-

charge components, measurements of electric conductivity and chemical analyses of water samples were carried out (Giertz 2004; Fass 2004). In addition, soil water dynamics were measured in a high temporal resolution (10 min.) on four plots with different land uses by using TDR-probes and tensiometers. In order to analyze the spatial variability of soil moisture 38 tube-access, TDR-probes were established in the Aguima catchment. The results of these measurements are published in Giertz (2004) and Fass (2004). In addition to these continuous measurements, several measuring campaigns concerning soil hydrologic properties were carried out from 2000 to 2003, such as infiltration measurements (Giertz 2004).

A detailed description of the measuring network of the Aguima catchment is given in Giertz and Steup (2008).

References

Fass T (2004) Hydrogeologie im Aguima Einzugsgebiet in Benin/Westafrika. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/fass_thorsten/fass.htm. Accessed 12 February 2010

Fink AH, Vincent DG, Ermert V (2006) Rainfall Types in the West African Sou-danian Zone during the Summer Monsoon 2002. Mon Weather Rev 134:2143-2164

Fink AH, Giertz S (2008) The hydro-meteorological network of the HVO. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 31-32. Department of Geography, University of Bonn, Bonn. http://www.impetus.uni-koeln.de/en/publications/digital-print-atlas.html. Accessed 12 February 2010

Giertz S (2004) Analyse der hydrologischen Prozesse in den sub-humiden Tropen Westafrikas unter besonderer Berücksichtigung der Landnutzung am Beispiel des Aguima-Einzugsgebietes in Benin (in German). Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/giertz_simone/giertz.htm. Accessed 12 February 2010

Giertz S, Steup G (2008) Acquiring a Database for Hydrological Process Analysis in the Aguima Catchment. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 39-40. Department of Geography, University of Bonn, Bonn. http://www.impetus.uni-koeln.de/en/publications/digital-print-atlas.html. Accessed 12 February 2010

Knippertz P, Fink AH (2006) Synoptic and Dynamic Aspects of an Extreme Springtime Saharan Dust Outbreak. Q J Roy Meteor Soc 132:1153-1177

Liu H, Foken T (2001) A Modified Bowen Ratio Method to Determine Sensible and Latent Heat Fluxes. Meteorol Z 10(1):71-80

Parker DJ, Fink AH, Janicot S, Ngamini JB, Douglas M, Afiesimama E, Agusti-Panareda A, Beljaars A, Dide F, Diedhiou A, Lebel T, Polcher J, Redelsperger JL, Thorncroft C, Wilson GA (2008) The AMMA radiosonde program and its implications for the future of atmospheric monitoring over Africa. Bull Am Meteorol Soc 89(7):1015-1027

Schrage JM, Fink AH, Ermert V, Ahlonsou ED (2006a) Three MCS Cases Occurring in Different Synoptic Environments in the Sub-Sahelian Wet Zone during the 2002 West African Monsoon. J Atmos Sci 63(9):2369-2382

Schrage JM, Augustyn MS, Fink AH (2006b) Nocturnal Stratiform Cloudiness during the West African Monsoon. Meterol Atmos Phys 95(1-2):73-86

Schrage JM, Fink AH (2007) Use of a Rain Gage Network to Infer the Influence of Environmental Factors on the Propagation of Quasi-Linear Convective Systems in West Africa. Weather Forecast 22(5):1016-1030

I-4.2 Weather and climate monitoring in Benin

M. Diederich and C. Simmer

Abstract

Several types of satellite and ground-based observations were combined to increase the reliability of climate data. The observations consisted of long-term rainfall measurements by a national network (starting in 1921), synoptic observations (starting in 1960), a dense research network of rainfall and climate observations in the Haute Vallée de l'Ouémé (HVO, since 1997), METEOSAT infrared images (since 1983), and space-borne measurements in the passive microwave spectrum (since 1998). They were used to cross-validate each other and to create synergetic data products. Finally, the data were integrated into a monitoring tool and information system that automatically treated the input data in order to create gridded estimates of rainfall, potential evapotranspiration, relative humidity, global radiation and temperature.

Keywords: Rain gauges, remote sensing, satellite measurements, meteorological data, temperature, evapotranspiration, Haute Vallée de l'Ouémé, Meteosat, synoptic messages, GTS, temperature, relative humidity, rainfall, global radiation

I-4.2.1 Introduction

When considering the hydrological cycle, knowledge of rainfall and evapotranspiration parameters is indispensable. For many applications, these data are needed for large areas (such as a river basin or an entire country) and for extended time periods (such as several decades). As mentioned in the preface, ground-based measurements of rainfall and evapotranspiration are sparse, or nearly absent, in the African tropics. The probability distribution, spatiotemporal correlation properties, and general strong variability of tropical convective rainfall make these parameters extremely difficult to assess for larger surfaces or high time resolutions. For example, the daily rainfall accumulation at one location may surpass 150 mm (corresponding to roughly 10% percent of mean yearly accumulation), with 80 mm falling within two hours, while slight or no rainfall may occur at a point only 20 km away from that location. If one is trying to estimate spatially integrated daily rainfall for a larger river basin using an observation network with a density lower than one gauge per 20 km, there are obvious problems. It is diffi-

cult to directly measure evaporation over large areas, as evaporation depends on a multitude of factors, such as temperature, relative humidity, wind speed, radiation and soil properties. Still, consistent and homogeneous estimations of these two parameters for past and present time periods, as well as for large areas, are needed for hydrological or agronomical modeling and decision-making.

To bypass these problems, rainfall and evapotranspiration retrieval algorithms based on satellite data have been developed within GLOWA-IMPETUS. Even if satellites cannot directly observe rainfall at ground levels, they provide regular and high-quality information on the extent and development of convective systems, with 30-minute temporal and roughly 5 km spatial resolutions (WMO 2008, II.8-23). Satellite data can, therefore, be used to provide a more accurate rainfall estimate for integrated surfaces and higher temporal resolutions than a rain gauge network alone, as long as the density of the gauge network is not high enough to observe the very localized convective events. There are several methods for estimating potential evapotranspiration (Allan et al. 1998). These methods differ mainly in the number of input parameters and time resolution that are required in the formulae, ranging from methods using only monthly temperature to methods using daily information on temperature, relative humidity, global radiation, wind speed, evaporation measured by class-A evaporation pans (for reference to measurement methods see WMO 2008), soil properties, and vegetation properties.

I-4.2.2 Meteorological observations in Benin used for data products

Archived records of daily rainfall in Benin were available starting in 1921, with a network of roughly 10 measurement sites that grew to roughly 100 stations by 2005. Most of these stations are standard rain gauges maintained by the Direction de la Météorologie Nationale (DMN), with few tipping bucket and weighing precipitation gauges installed recently. The data quality of these measurements varies strongly from station to station and over time, and not all stations provide regular daily accumulations from 06 UTC to 06 UTC. Reliable stations were identified if daily rainfall data was used in any analysis. Data originating from six synoptic stations (see fig. I-4.2.1, left panel) provided, among other parameters, relatively regular temperature and humidity measurements that were used in the meteorological products of IMPETUS, beginning with the year 1983 (Diederich and Simmer 2008). These stations also provided class-A evaporation measurements and sunshine duration for recent years, but these data were only used for validation purposes and not in the products themselves, because they did not cover the entire time period.

Hourly rainfall observations made at the same synoptic stations since the mid-1950s were also available. These data were derived from digitalized gauge recorder charts (Fink et al. 2008). They were not integrated directly into the products because of the aforementioned high spatial variability of hourly rainfall fields; they were instead used to verify and calibrate the probability density function of hourly

rain intensities. More observations of meteorological variables with high quality and temporal resolution, created by several projects and institutions (see sect. I-4.1), were used for the validation and calibration of meteorological IMPETUS products. However, the temporal or spatial extents of these observations were too small for integration into nationwide monitoring, which would have caused the homogeneity of the output to suffer.

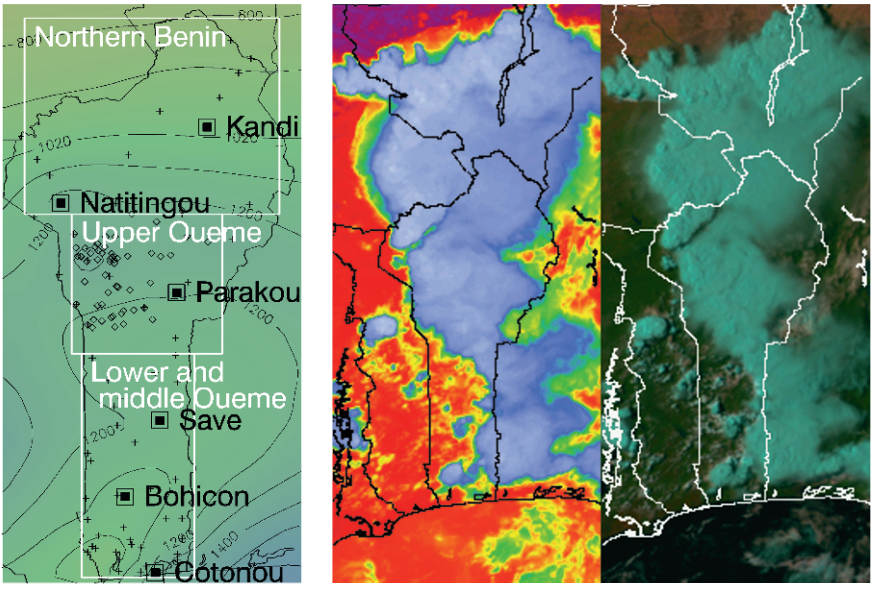

Fig. I-4.2.1: Left panel: Isohyet map of mean yearly rainfall between 1921 and 2005, with locations of synoptic stations indicated by squares, daily rain measurement sites of DMN indicated by crosses, and rain gauges that were operated by IRD/CATCH/AMMA/ IMPETUS represented by diamonds. The latter stations are identical to those shown in fig. I-4.1.1. Middle and right panel: Image of a squall line occurring on 30 August 2004 17 UTC taken by MSG-1 in the infrared spectrum at 10.8 µm (middle) and composite image of the visual spectrum at 0.6 and 0.8 µm (right).

The geostationary METEOSAT First Generation (MFG described in EUMETSAT 1996) and METEOSAT Second Generation (MSG, described in EUMETSAT 2001) satellites based at 0° longitude represent another valuable source of meteorological information. Although they do not directly measure any of the desired parameters, the satellite images taken in the visual and infrared spectrum contain cloud information (see fig. I-4.2.1, middle and right panel) that is linked to the meteorological observations made on the ground. The images can be used to enhance the quality of meteorological measurement archives by cross-checking them with satellite observations to identify paradox information, or to correct obvious wrong time-referencing in some of the observations. In combination with hourly observations of temperature, relative humidity, global radiation, and rainfall made

by climate stations between 2001 and 2006, retrieval algorithms using satellite images and synoptic messages as input to derive the parameters for the entire region could be calibrated and tested. Meteorological satellite images since 1983 covering Benin were available in half hourly increments at about 6 km resolution (METEOSAT 2 to 7), as well as images from 2004 onward in 15 minute increments at 3 km resolution (MSG). These images can be used to enhance and generate estimates of these parameters with the archived synoptic data for this time period, and they can also be used to generate the same parameters in near real time using a MSG receiver station. This receiving station makes it possible to generate the satellite images and the synoptic measurements through the Global Telecommunications System (GTS, described in WMO 2007) in near real time.

In sum, the following measurements were available to create meteorological monitoring products for Benin:

- daily rainfall observations from 1921 to present at roughly 10 to 80 sites, available for processing at the DMN with several months' delay,
- synoptic measurements at six locations starting in the 1960s, available via GTS with a few minutes' delay,
- high-resolution ground observations by a dense gauge network and climate stations in the Haute Vallée de l'Ouémé (HVO) since 1997, accessible with a month delay,
- archived MFG satellite images from 1983 to 2006, and MSG images from 2004 to present, accessible via internet or satellite receiver with a 15-minute delay.

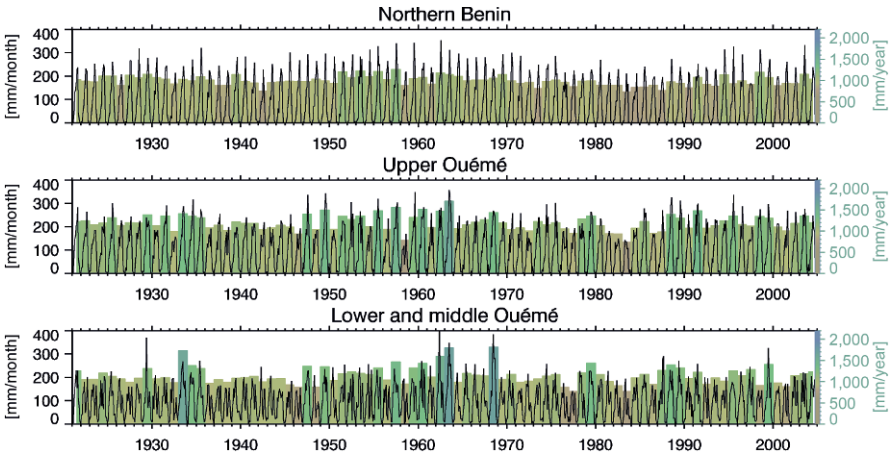

Fig. I-4.2.2: Monthly and yearly cumulated rainfall in 3 regions (see boxes in figure I-4.2.1a for a spatial reference of the three regions) of Benin from 1921 to 2005. The black lines represent monthly rainfall totals (axis on the left), and the colored bars represent yearly totals (axis and color coding on the right). More details are given in Diederich and Simmer (2008).

I-4.2.3 Data products and monitoring

The data availability allowed for the creation of several different data products, some of which can be produced in near real-time:

1. Monthly rainfall accumulations, gridded at 0.1 degree latitude/longitude resolutions, starting in 1921. The DMN gauge network was interpolated using kriging techniques (Krige 1951). Due to the low density of the network and unreliable time-referencing of some of the observations, daily observations where accumulated to monthly sums. Because of the low gauge density, particularly for earlier years, this product is recommended for use in resolutions lower than 0.1 degree, such as for larger regions as shown in figure I-4.2.2.

2. Hourly and daily rainfall accumulations gridded at 0.1 degree latitude/longitude resolutions, starting in 1983. In order to derive rain fields with higher temporal resolution, METEOSAT infrared images taken at 10.8 μm wavelength in 30-minute intervals were used to identify times and regions with possible rainfall. Cloud top temperature and cloud stages (growing or decaying) are visible to the satellite and are fairly good indicators of the probability of rainfall occurrence, but they hardly allow for the estimation of rain intensity. Typical rain rates were assigned to cloud parameters measured by satellite using multiple regression, calibrated using observations between 1983 and 2005. Even if the satellite-derived rainfall alone exhibits poor quantitative agreement when compared to single gauge measurements, the satellite estimate for a larger area is still a better estimate than one obtained from a low-density gauge network. The quality of satellite rainfall estimates can be further enhanced by combining them with ground measurements, but this introduces a delay into the otherwise real-time availability of satellite data. The advantage of merging satellite and gauge data in this way is that measurement gaps and incomplete gauge data are filled while conserving the advantages of both high-resolution satellite and quantitatively accurate gauge measurements.

3. Hourly and daily estimates of global radiation, temperature, and relative humidity gridded at 0.1 degree latitude/longitude resolution, starting in 1983. Global radiation can be estimated by calculating incoming solar radiation according to time and geographic location, and then deriving the extinction by clouds through the meteorological satellite data. Temperature and relative humidity measurements are provided by the 6 synoptic stations at 6 hourly intervals. The spatial variability of these two parameters is far smaller than that of rainfall or global radiation, and interpolated values are therefore much more realistic. The interpolation was complimented by adding spatial and temporal variability in between observations, using standard assumptions regarding decrease of temperature with height, the diurnal cycle, and temperature anomalies produced by rainfall and cloudiness. Similarly, the relative humidity measurements at the same stations were interpolated by transforming them into water vapor pressure, interpolating them by ad-

ding standard assumptions on their behavior with height, and transforming them back into relative humidity using the previously-derived temperature data. These parameters can be derived in near real time if fed by a satellite receiver that provides METEOSAT infra-red images and synoptic GTS messages.

4. Daily estimates of potential evapotranspiration gridded at 0.1 degree latitude/longitude resolution, starting in 1983. The approach chosen to derive this parameter was to apply the Penman formula as recommended by the Food and Agriculture Organization (FAO) (Allen et al. 1998) to the daily values given above.

Using these methods, a merged observational dataset of 0.1° latitude/longitude gridded estimates of rainfall, global radiation, temperature, relative humidity (hourly resolution), and potential evapotranspiration (daily resolution) was generated for the entire territory of Benin. The resulting estimates do not have the quality of hourly measurements made by a well-attended meteorological observation site at each pixel, but are nonetheless more accurate and homogeneous in quality than simple interpolation techniques due to the data merging. These data also has higher resolution and accuracy than atmospheric model reanalysis products, due to more input observation data.

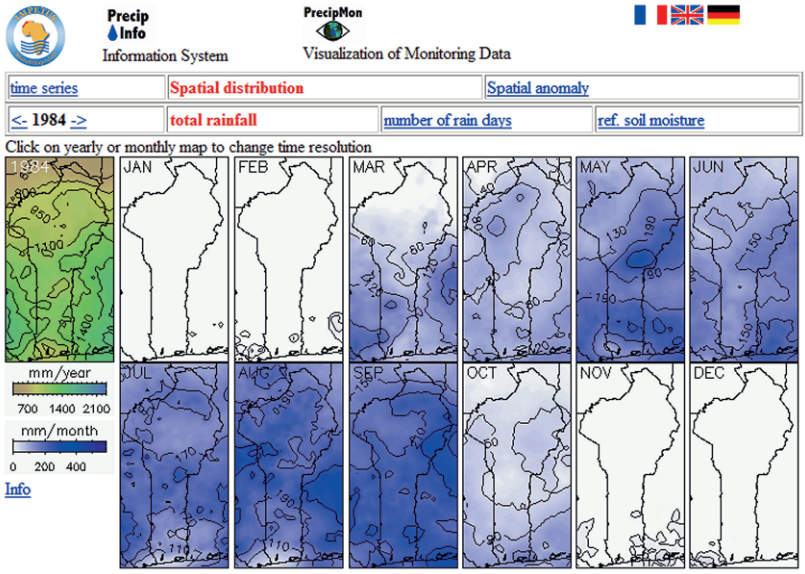

Fig. I-4.2.3: Example of representations of monthly rainfall totals in the HTML interface.

The retrieval algorithms have been integrated into a monitoring tool with a graphical user interface written in the Interactive Data Language (IDL). It can be executed in an IDL-Virtual Machine environment, which may be used without a

costly license. The hourly near real-time data is produced using only MSG images and synoptic messages for input, both of which can be obtained by the same satellite receiver. Data are added to the archive after it is generated, where it can be extracted, re-sampled, and visualized using a tool that is also programmed in IDL. The data is also visualized for quick reference as maps or time series in the form of webpages (see figs. I-4.2.3 and I-4.2.4) which are automatically generated by the same software.

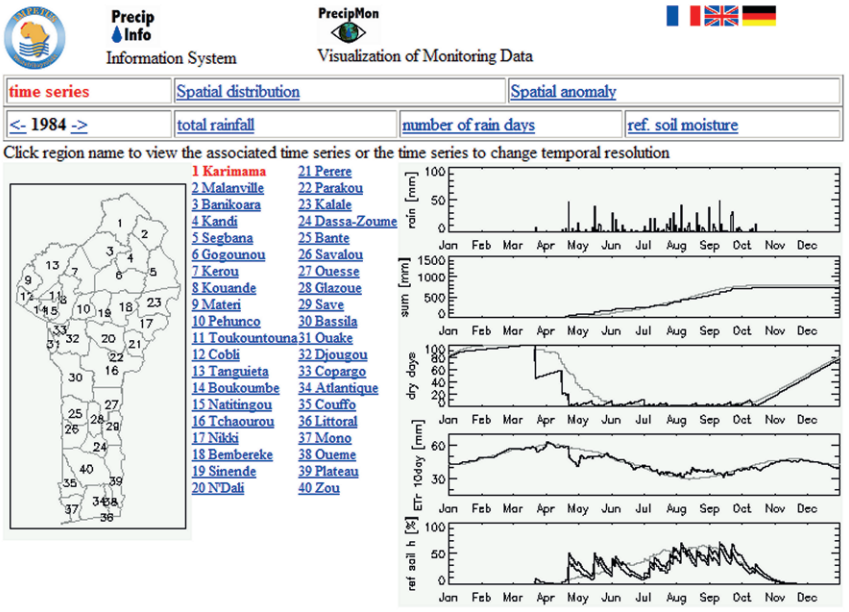

Fig. I-4.2.4: Example of representations of time series for chosen areas in the HTML interface.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) FAO Irrigation and Drainage Paper No. 56, Crop evapotranspiration (guidelines for computing crop water requirements). FAO, Rome

Diederich M, Simmer C (2008) Observations of past and present rainfall in Benin. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 19-20. Department of Geography, University of Bonn, Bonn

EUMETSAT (1996) The Meteosat System. Technical Documentation EUM TD05, Darmstadt

EUMETSAT (2001) Meteosat second generation-system overview. EUM TD07, Darmstadt

Fink A, Pohle S, Hoffmann R (2008) Spatial and Temporal Rainfall Climatologies of Benin. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 21-22. Department of Geography, University of Bonn, Bonn

Krige DG (1951) A statistical approach to some basic mine valuation problems on the Witwatersrand. J Chem Metall Mining Soc S Afr 52(6):119-139

WMO (2007) Manual on the Global Telecommunication System, Volume I. WMO-No. 396, 2007 edition

WMO (2008) Guide to Meteorological Instruments and Methods of Observation. WMO-No. 8, Seventh edition

I-4.3 Hydro-meteorological measurements in the Drâa catchment

O. Schulz, M. Finckh, and H. Goldbach

Abstract

Taking into account the landscape variability within the Upper and Middle Drâa basin, a test site approach was chosen to provide data for several scientific disciplines. A climate and vegetation monitoring network was established along the temperature and aridity gradient between the sub-humid High Atlas Mountains and the former end lake of the Middle Drâa in a pre-Saharan environment. The gathered data complete the existing administrative database and allow for precise analyses and modeling of environmental processes, even in the still "unknown" and remote high mountain region at the upper end of the investigation area.

Keywords: Test site approach, ecological zones, aridity gradient, high mountain region, desert, climate, geology, vegetation, monitoring network, grazing exclosure, hydro-meteorological station, automatic weather station, interdisciplinary demands, database, precipitation, snow cover

I-4.3.1 Introduction

The Drâa basin comprises the transition zone from sub-humid oromediterranean scrublands to arid Saharan deserts. From the catchment divide in the High Atlas and southward, vegetation zones are located along a gradient of increasing temperature and decreasing precipitation. This gradient includes an increasing interannual coefficient of variance for precipitation (Knippertz et al. 2003), while the rainy season generally lasts from autumn to spring, with a bimodal distribution at a minimum in January (Schulz 2008a). About 93% of the area is covered by range lands and is used for extensive grazing by mobile and sedentary pastoralists. Stocks (and thus grazing pressure) have strongly increased in the High Atlas over the last few decades (Chiche 2007). Merely 1.4% of the area is used for irrigated agriculture in the oases along the permanent streams.

At the beginning of the project in Southern Morocco, a test site approach was chosen, and a monitoring transect was installed to cover the landscape variability within the Upper and Middle Drâa basin (30,000 km²) by defining representative areas for field research. Since climate information is a prerequisite for the analysis of environmental processes, a special focus was placed on regions not covered by

the climate monitoring network of Moroccan administrations. Table I-4.3.1 gives information about the hydro-climatic station network of the *Agence du Bassin Hydraulique* (ABH) in the Upper and Middle Drâa basin. These hydro-climatic stations are not placed at high elevations because the stations also measure runoff, meaning that stations must be located in valleys (Schulz et al. 2008c). Therefore, we stated a lack of climate information for mountain regions. Since these regions – especially parts of the High Atlas Mountains within the Drâa basin – experience increased precipitation sums of up to 800 mm per year (Schulz 2008b), a reliable estimation of the basin wide water input cannot be made solely on the basis of this administrative station network. Furthermore, local heavy rainfall events are not recorded in remote regions, complicating hydrological analysis, modeling and flood forecasting. The IMPETUS climate network on the project test sites since 2001 complements measurements done by ABH Souss-Massa-Drâa, as well as the climate stations of the ORMVAO (*Office Régional de Mise en Valeur Agricole de Ouarzazate*) within the oases along the Upper and Middle Drâa valley. The only first order meteorological station of the *Direction de la Météorologie Nationale* in the Drâa basin is located in Ouarzazate.

Table I-4.3.1: Hydro-climatological station network of the *Agence du Bassin Hydraulique* in the Upper and Middle Drâa basin (Source: ABH Souss-Massa-Drâa 2004, formerly *Service Eau Ouarzazate*).

Station	River (Oued)	Elevation	Annual precipitation	Commissioning year
Agouillal	El Mellah	1,220 m	-	1976
Agouillal	Imini	1,647 m	270 mm	1969
Ait Mouted	Dadès	1,545 m	167 mm	1940
Amane-n-Tini	Ouarzazate	1,170 m	109 mm	1982
Assaka Tafounante	Ait Douchène	1,380 m	135 mm	1975
Ifre	M'Goun	1,498 m	152 mm	1940
Imdghar-n-Izdar	Amagha	1,502 m	144 mm	1974
Mansour Eddahbi dam	Reservoir	1,100 m	104 mm	1973
M'Semrir	Dadès	1,942 m	218 mm	1940
*Ouarzazate	-	1,140 m	116 mm	1940
Taharbilt	Ait Douchène	1,226 m	115 mm	1978
Tamdrouste	Iriri	1,245 m	117 mm	1983
Tinouar	Dadès	1,136 m	103 mm	1974
**Zagora	Drâa	703 m	62 mm	1940

*The meteorological station Ouarzazate is operated by the National Moroccan Weather Service.
**The station Zagora is the only ABH station in the Middle Drâa Valley.

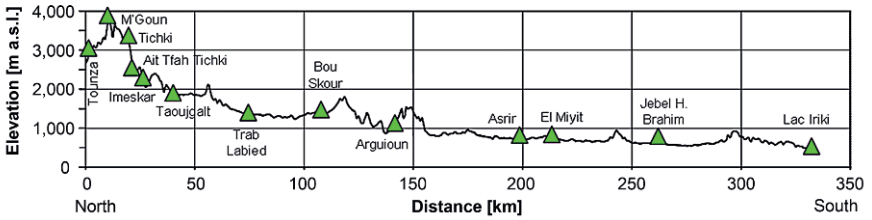

Fig. I-4.3.1: Topographical profile of the 13 project test sites and automatic weather stations (Source: Schulz 2008a).

Several disciplines worked together at the project test sites, requiring adjustment of the varying demands of environmental sciences (geology, climatology, hydrology, plant ecology, remote sensing, and agriculture) and social sciences (cultural anthropology and agro-economy). The implementation of test sites in different landscape units (such as the high and low mountain ranges of the High Atlas and Antiatlas/Jebel Saghro), basins and valleys followed the main ecological gradients (temperature and aridity) and geological macro-units. The Drâa basin experiences climatological, geological and botanical shifts along the topographical profile from the Central High Atlas Mountains (4,071 m asl) via the Antiatlas chain – the transitional zone to the Sahara desert – to the former end of Lake Iriki in the Middle Drâa (450 m) (see fig. I-4.3.1). Variability in pedology and land use was considered in the choice of test sites as much as possible (Schulz 2008a). Beyond the test sites, special disciplinary surveys were conducted for distributed data collection, such as soil and water sampling. Mapping of characteristic vegetation and land cover patterns served as ground truths for upscaling and regionalization methods by using remote sensing and modeling. Some measurements at the test sites are shown in figure I-4.3.2, and the location of the test sites within the monitoring network of the Drâa basin is shown in figure I-4.3.3. For details on the vegetation units of the Drâa basin, compare section II-5.1 and Finckh and Poete (2008).

I-4.3.2 Meteorological measurements at the test sites

A typical test site includes a fenced terrain of 1,500 m² with an automatic weather station (AWS) and permanent plots for botanical monitoring. Additional reference plots outside of the fence quantify the impact of land use on vegetation, such as grazing pressure and firewood gathering. There is no botanical monitoring at the highest station of M'Goun (3,850 m) because sparse scree vegetation above 3,500 m is considered to be of minor ecological and pastoral importance.

The AWSs are equipped with a number of instruments that differ between the test sites according to environmental and scientific demands. Standard equipment includes instruments to measure air temperature and humidity, soil temperature at

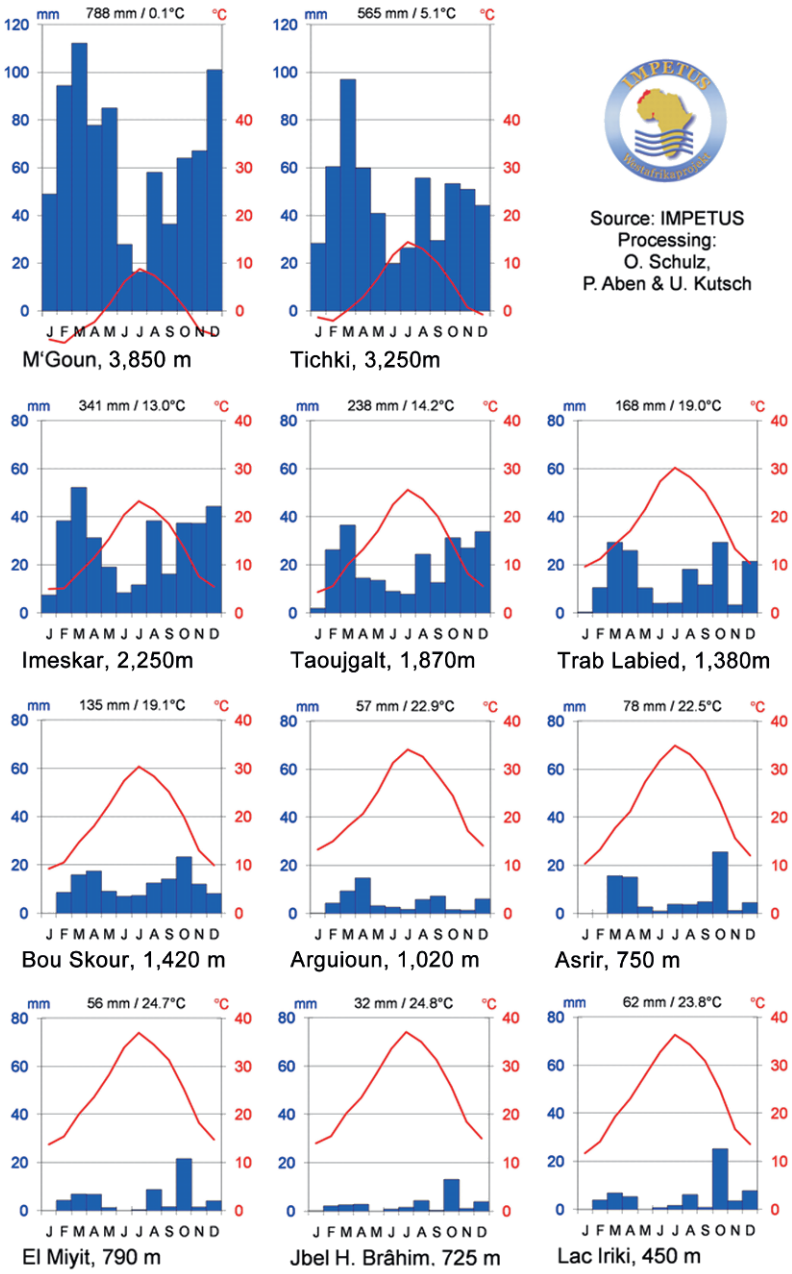

Fig. I-4.3.2: Precipitation sums and temperature means at eleven automatic weather stations of the IMPETUS climate monitoring network in the Drâa basin. Data values are averages for the period 2001-2006 (Source: Schulz 2008a). For locations see figure I-4.3.1 and I-4.3.3.

different depths, global radiation, wind speed, wind direction and precipitation. Some central stations of the monitoring network also measure soil humidity, soil heat flux and net radiation; on a second level, some stations monitor air temperature, humidity, and wind speed. Furthermore, since detailed analyses focus on snow cover and plant ecology, additional instruments are installed to measure snow depth, snow pack, and snow surface temperature (High Atlas) or photosynthetically active radiation (Asrir oasis, Lake Iriki). All stations are controlled by a data logger and are energized by battery and solar panels.

Following the gradient from north to south, all test sites are briefly presented with their characteristics, along with some results regarding precipitation measurements. The M'Goun test site, the highest point of the monitoring network, is located on the southern slope of the M'Goun range (High Atlas) at 3,850 m altitude, near the crest. At this altitude, the water equivalent of winter snowfall exceeds the liquid precipitation sum of the rest of the year and serves as an important water reserve for the Drâa basin. The minimum air temperature recorded was -24°C, and the maximum snow depth was 1.5 m. Other precipitation measurements in this highest mountain zone do not exist, but extrapolations of Moroccan water and hydrology authorities report an annual sum between 500 mm (Youbi 1990) and 600-800 mm (Gaussen et al. 1958). The latter measurement may be corroborated with our measurements (6-year-average of 800 mm). Knowledge of the radiation, temperature, and humidity conditions in this zone was a prerequisite to understanding and modeling cycles of freezing and thawing, snow depletion processes (melt and sublimation) and timing. The geologic underground is Jurassic limestone, with Triassic red sediments and basalts found further down in the valleys. When the test site was installed, vegetation was considered absent and no permanent plot was established. To our surprise, three scree-specialists (*Platycapnos saxicola, Linaria tristis, Veronica rosea*) began spreading in the small fence around the climate station. Nonetheless, intensive pasturing ends around 3.500 m asl.

The Tichki test site is located on the same mountain range as the M'Goun station, at an altitude of 3,250 m and 10 km to the east. This area is the middle snow zone, where solid and liquid precipitation levels are nearly equal. The geologic situation of dominating Jurassic limestone is similar to the M'Goun test site. More inclined scree slopes alternate with less inclined and soil-covered slopes. The vegetation is dominated by oromediterranean thorny cushion shrubs (seven species from four families) and permanent grasses on stable slopes, and by debris specialists on scree. Juniper (*Juniperus thurifera*) was presumably eliminated by humans at this site, but single individuals can still be found in the surroundings. The percentage of Moroccan endemic species is high.

On the northern slope of the same M'Goun mountain range at 3,000 m, the Tounza test site represents a slightly inclined terrain, which was assumed to be wetter than other test sites on the southern slope. This assumption was based on main atmospheric circulation patterns, with the transport of moisture from the northwest and a blocking function of the main mountain ranges. Since the Jebel



Fig. I-4.3.3: Annual precipitation sums, measurement stations of the IMPETUS project and the ABH Souss-Massa-Drâa/*Service Eau de Ouarzazate* in the Upper and Middle Drâa basin (Source: Schulz 2008b). The map is based on a statistical analysis of the different record lengths (ABH 1984-2006; IMPETUS 2001-2006).

Ghat range in the further northwest blocks the north-west incident flow, the initial assumption could not be verified by precipitation measurements at this location. Nevertheless, the soil above the Jurassic limestone is deeper and contains more moisture than soil from southern-oriented test sites. Vegetation is of the oromediterranean type, with thorny cushion shrubs, perennial grasses, and hemicryptophytes. Perennial grasses, especially *Festuca* ssp., are increasingly important in the exclosure and may out-compete dwarf-shrubs in the long run.

Near the top of a low mountain ridge in the lower Jurassic limestone zone, the Imeskar (or Ameskar) test site was established at 250 m above the Ameskar valley. The area is under sylvopastural use, especially for sheep and goat grazing and domestic firewood collection. At this elevation (2,250 m), vegetation is an open juniper sagebrush steppe (three *Juniperus* species, three *Artemisia* species, three *Stipa* species, *Teucrium mideltense*) with Mediterranean maquis elements (e.g., the genera *Thymus, Genista, Sideritis, Helianthemum*). Some holm oaks (*Quercus rotundifolia*) and ashes (*Fraxinus xanthoxyloides*) still remain at the shadowy northern slopes and close to the valley floor. This test site represents the southern limit of Mediterranean forest ecosystems in the High Atlas, but tree regeneration is limited to years with exceptionally wet conditions. *Stipa* species increase continuously in the exclosure. The zone represents the lower snow zone with only a few days of frost and snow cover. Less than 20% of annual precipitation occurs in the form of snow. Based on data from the M'Goun, Tichki and Imeskar stations, the mean annual precipitation gradient for the high mountain zone was calculated based on altitude. Using these data and data from other stations in the Drâa basin (ABH Souss-Massa-Drâa), a gradient was established that is closely correlated with altitude. The results serve as a basis for the calculation of regional precipitation maps (see fig. I-4.3.3) and also serve as input for hydrological models in the project.

The Ait Tfah Tichki test site represents the climatic conditions of a supramediterranean mountain valley at 2,300 m. Due to uplift and erosion processes during the Cenozoic age, Jurassic limestone, Triassic red sediments and basalts can be found side by side near the valley ground. Apple trees, walnut trees, cereals, and vegetables on irrigated terraces characterize the area in the vicinity of a little village. This station was used for detailed agricultural analysis and modeling.

The wide intramountainous valley of Ait Toumert opens away from the principal mountain chain. At the footslope of an alluvial fan, the Taoujgalt test site is placed at an elevation of 1,870 m. The valley ground consists of Pliocene weathered conglomerates. Precipitation declines along the gradient (~ 250 mm) and snow fraction is estimated to be 5% of the annual precipitation sum. The vegetation corresponds to an Ibero-Mauretanian sagebrush steppe dominated by *Artemisia herba-alba*, *A. mesatlantica*, *Teucrium mideltense* and *Stipa parviflora*. The area is the main grazing ground for village sheep herds and is an important migration stopover during spring and autumn for transhumant pastoralists with sheep and goats. The gathering of firewood has a strong impact on the steppe vegetation, especially in vicinities of larger villages between Allemdoun and Ait Youb.

Halfway between the foothills of the High Atlas and the Skoura oasis, the Trab Labied test site (1,380 m) represents the environmental conditions of the Ouarzazate basin. This site is placed on a large fan of alluvial sediments with sparse vegetation (pre-Saharan *Hammada scoparia*-steppe). *Farsetia occidentalis* and the C4-grass *Stipagrostis obtusa* dominate in small depressions. The annual grass *Stipa capensis* develops strongly during humid spring seasons, while the flowering of *Hammada scoparia* dominates the autumn aspects and pastures at this site. The climate station is equipped with instruments at two levels to calculate energy balances.

The Jebel Saghro – the Precambrian part of the Antiatlas – rises up as a southern barrier to the Basin of Ouarzazate. Here, the Bouskour test site (1,420 m) lies in a hilly landscape that represents both hydrologic and geomorphologic units of Precambrian magmatites and pliocenic sediments. Vegetation is a *Hammada scoparia -Convolvulus trabutianus* rock-steppe. The area is an important winter pasture for transhumant nomads from the Ait Zekri fraction. The exclosure allows for a significant increase in biomass and species richness. Grazing-sensitive species, such as *Stipa parviflora*, reestablished in the exclosure. The absence of grazing changed interspecific competitiveness and thus spatial vegetation patterns. Along the testsite transect, we find the peak of species richness at this site due to divergent therophyte guilds and the overlapping of Ibero-Mauretanian and Saharan biomes.

From a climatologic point of view, the data from this station confirm the assumption that precipitation rises again from the Basin of Ouarzazate to the Antiatlas Mountains. Both stations, Trab Labied and Bouskour, experienced 140 mm per year, which cannot be reached at either the Drâa Hydrological Service stations or the Ouarzazate WMO station in the lowest parts of the basin (100-120 mm, cf. the stations Ouarzazate, Tinouar and Mandsour Eddahbi Dam in table I-4.3.1).

All tributaries of the upper wadi Drâa are unified in the Mansour Eddahbi reservoir on the northern foot of the Antiatlas. From here, the wadi Drâa cut into the Antiatlas and arrives in the Middle Drâa valley with its palm oases along the river. Above the first palm oasis, the Arguioun test site is located near the town Agdz on a northern-oriented slope in a middle elevation (1,020 m). The test site represents the geomorphologic, hydrologic and plant ecology characteristics of the widely-distributed Cambrian and Ordovician sediments of the Antiatlas, with semi-desert vegetation that is dominated by dwarf-shrubs. Saharan therophytes play an important role during spring seasons. Permanent degradation features are not perceptible at this test site, and precipitation is reduced to 80 mm per year.

Near the city of Zagora further downstream, the Asrir station is installed in the third palm oasis of Ternata on an experimental site of the ORMVAO. A special focus was placed on the palm stand climate. Additionally, vegetables and lucerne are cultivated.

Within the southern Antiatlas, an intramountainous basin opens west and east of the wadi Drâa. On the eastern side, the El Miyit test site (790 m) in the great basin south of Zagora represents the basin in the southern area of the sedimentary Antiatlas chains at the Saharan border. The basin with quaternary wadi gravel deposits is surrounded by Jebel Bani, a cuesta of Palaeozoic quartzites. *Acacia rad-*

diana dominated savanna vegetation is concentrated in mostly waterless drains. The site constitutes the northernmost known population of the Sahelian tree *Maerua crassifolia* in Morocco. Mean annual precipitation can reach up to 55 mm. Runoff in the drains is produced only during severe rainfall events.

The last mountain chain located north of the now westward-turning wadi Drâa is the cuesta of Jebel Bani. It surrounds the basin of Tagounite in a northern and a southern ridge, the latter called Jebel Hssain ou Brahim. The homonymous test site (770 m) is separated into a botanical monitoring site and a climate station that is installed half a kilometer away, since local topography alters general wind direction. Vegetation is dominated by Saharan therophytes, e.g., *Fagonia longispina* and *Sclerocephalus arabicus*. Few dwarf shrubs and geophytes can tolerate the extreme climate conditions. The southern, gently-inclined cuesta slope serves as a heating surface, which is recorded in forms of the highest air and soil temperatures of the project's network. The lowest mean annual precipitation of 36 mm is due to increased evaporation.

The former end lake of the Middle Drâa, Lake Iriki, has been mostly dry since the Mansour Eddahbi Dam (near Ouarzazate) was brought into service in 1973, restricting discharge to periods of water releases (*lâchers*). Today, a salt clay pan in the Iriki National Park is located on the former lake bed, where the Iriki test site (450 m) forms the end point of the project's monitoring network. The site is representative of the Saharan border climate without the effect of topography. Where vegetation cover is present, Halophytes dominate. The weather station is placed in a sparse and apparently relictic *Tamarix amplexicaulis* stand. The *Tamarix* population is dying back since the beginning of our monitoring in spring 2001. Over the whole monitoring period, therophytes developed only once, after spring rains in 2003. In the soil, the rhizomes of former reed beds from the pre-Mansour Eddahbi lake ecosystem are still noticeable. The annual precipitation sums up to 50 mm with few but abundant rainfall events, which sometimes enable local farmers to cultivate wheat without additional irrigation.

I-4.3.3 Hydrological and other measurements

Water level gauges were installed at the southern test sites at the beginning of the project. The objective was to monitor occasional surface runoff generated during local rainfall events in small, well-defined catchments as part of the soil hydrological investigations. One gauge was installed in the high mountain valley of Assif-n-Ait Ahmed, where perennial runoff exists (catchment size: 50 km²). At the end of the first project phase, all gauges were moved to high mountain valleys to support detailed hydrological modeling in the upper M'Goun region, upstream from the administrative hydro-climatological station at Ifre (see table I-4.3.1). The outcomes of measurements and modeling are presented in Weber (2004) and Schulz (2006). Detailed hydrogeological analyses were carried out by Cappy (2006) in

the Upper Drâa basin, including water quantity and quality of springs and wells. Additionally, isotopic concentrations were compared to those of precipitation water samples taken at the test sites. Based on these results, main groundwater recharge zones can be deduced (Cappy 2006).

References

Cappy S (2006) Hydrogeological Characterization of the Upper Drâa Catchment: Morocco. Bonn. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/ math_nat_fak/2007/cappy_sebastien. Accessed 29 September 2009

Chiche J (2007) History of Mobility and Livestock Production in Morocco. In: Gertel J, Breuer I (eds) Pastoral Morocco - Globalizing Scapes of Mobility and Insecurity. Nomaden und Sesshafte, Vol. 7, pp. 31-59. Ludwig Reichert Verlag, Wiesbaden

Finckh M, Poete P (2008) Vegetation Map of the Drâa Basin. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 31-32. Department of Geography, University of Bonn, Bonn

Gaussen H, Debrach J, Joly F (1958) Précipitations annuelles. Atlas du Maroc. Notes explicatives, Planche No. 4a. Rabat

Knippertz P, Christoph M, Speth P (2003) Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorol Atmos Phys 83:67-88

Schulz O (2006) Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M'Goun, Zentraler Hoher Atlas (Marokko). Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2007/schulz_oliver. Accessed 29 September 2009

Schulz O (2008a) The IMPETUS Climate Monitoring Network. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 17-18. Department of Geography, University of Bonn, Bonn

Schulz O (2008b) Precipitation in the Upper and Middle Drâa Basin. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 19-20. Department of Geography, University of Bonn, Bonn

Schulz O, Busche H, Benbouziane A (2008c) Decadal Precipitation Variances and Reservoir Inflow in the Semi-Arid Upper Drâa Basin (South-Eastern Morocco). In: Zereini F, Hötzl H (eds) Climatic Changes and Water Resources in the Middle East and North Africa, pp. 165-178. Springer, Berlin-Heidelberg

Weber B (2004) Untersuchungen zum Bodenwasserhaushalt und Modellierung der Bodenwasserflüsse entlang eines Höhen- und Ariditätsgradienten (SE Marokko). Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/weber_benedikt. Accessed 29 September 2009

Youbi L (1990) Hydrologie du Dadès. Ministère de l'Agriculture et de la Reforme Agraire, Office Régional de Mise en Valeur Agricole de Ouarzazate. Ouarzazate





5 Atmosphere

5.1 Meteorological processes influencing the weather and climate of Benin

5.1.1 Introduction

5.1.2 Air masses, convergence zones, and wind systems

5.1.3 The seasonal cycle

5.1.4 Interannual-to-decadal rainfall variability

5.1.5 The role of sea surface temperatures in West African rainfall

5.1.6 The role of greenhouse gases and aerosols in West African rainfall

5.1.7 Conclusions

5.2 Meteorological processes influencing the weather and climate of Morocco

5.2.1 Introduction

5.2.2 Winter precipitation in Morocco: How is Moroccan rainfall connected to global scale climate variability?

5.2.3 Summer precipitation and convective density currents

5.2.4 Conclusions

I-5 Atmosphere

A. H. Fink

Keywords: Haute Vallée de l'Ouémé, Drâa catchment, North Atlantic Oscillation, El Niño-Southern Oscillation, sea surface temperature, tropical-extratropical interactions, aerosols, climate models, Circulation Weather Types

The *Haute Vallée de l'Ouémé* (HVO) in Benin is located in a tropical wet and dry sub-humid climate, whereas the Drâa catchment is situated in the mostly semi-arid subtropical climate zone of North Africa (see sect. I-3.4). In this chapter, the major meteorological processes including their seasonal cycles are described, which determine the weather and climate of Benin and Morocco. A better understanding of the dynamics of rainfall-bearing weather systems and how they are impacted by large-scale forcing mechanisms – such as the North Atlantic Oscillation (NAO), the El Niño-Southern Oscillation (ENSO), sea surface temperatures (SSTs) of tropical oceans, atmospheric aerosols, or land surface conditions – are instrumental in explaining and modeling rainfall variability at temporal scales ranging from days to decades. To approach this goal, meteorological research within IMPETUS has focused on identifying different types of rainfall systems in Benin and quantifying their contribution to annual rainfall. This has been complemented by studies that have tried to determine the percentage of variance in long-term rainfall fluctuations which is attributable to external factors such as SSTs, aerosols, and greenhouse gases.

In Morocco, an alternative approach has been pursued: Circulation Weather Types (CWTs) were defined and their relation to rainfall in three Moroccan homogeneous rainfall regions was investigated. The impact of NAO and ENSO on both the CWTs and Moroccan rainfall was also examined. One outstanding and novel discovery of understanding the processes governing rainfall variability is the dominant role of tropical-extratropical interactions (TEI) and tropical moisture sources for rainfall south of the Atlas Mountains' main divide. As will be detailed in section II-3.1, the appreciation of factors determining regional Climate Change is one of the four pillars of regionalizing Climate Change projections from global climate models. The pertinent role of TEIs and their poor representation in climate models lead to the use of an alternative climate scenario for the Middle Drâa valley in IMPETUS than the 'rainfall reduction scenario' suggested by climate models (see sect. II-3.1). A hierarchy of climate models has been applied within IMPETUS to project future plausible pathways of Climate Change in both catchments. Section II-3.1 describes these results in detail.

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I-5.1 Meteorological processes influencing the weather and climate of Benin

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Abstract

The major rain-bearing weather systems in Benin are presented along with some of their major characteristics, their contribution to annual rainfall in 2002, and their seasonal cycles. The long-term variability in annual rainfall and in days with (strong) rainfall is shown for three regions in Benin. The relation of rainfall fluctuation in these three Beninese regions to the larger-scale variability at the Guinea coast and Central Sahel is discussed. Finally, the large-scale forcing mechanisms of interannual to decadal rainfall variability in Benin and West Africa are reviewed.

Keywords: Aerosols, African Easterly Jet, African Easterly Waves, Azores High, climate model, convective part, dipole years, diurnal cycle, dry season, El Niño, evapotranspiration, greenhouse gases, Harmattan, heat low, instability shower, Inter-Tropical Convergence Zone, Inter-Tropical Front, land-sea breeze circulation, little dry season, Mesoscale Convective System, monsoon air mass, monsoon rains, monsoon onset, monsoon withdrawal, monsoonal south-westerlies, non-dipole years, Organized Convective System, pre-monsoon season, rainfall types, rainy season, Saharan air mass, sea-surface temperature, Soudanian zone, squall line, teleconnection, Tropical Easterly Jet, tropical extra-tropical interactions, Tropical Plume, Sahel drought, stratiform part, summer monsoon, Standardized Precipitation Index

I-5.1.1 Introduction

Tropical West Africa is known for its variable rainfall climate, often exceeding the rainfalls fluctuations of many other places on earth. The most recent drought in West Africa commenced in the early 1970s and peaked in the mid-1980s (see sect. I-3.4) and has prompted numerous studies on the causes of rainfall reduction (Nicholson 2001). The results presented in this section focus on rainfall-bearing weather systems, and the major characteristics and seasonal cycles of each system are introduced. The interannual to decadal rainfall variability for Benin is discussed and examined in the context of simultaneous rainfall fluctuations in Sahel and the Guinea coast. Finally, the meteorological factors that determine year-to-year and decadal-scale rainfall variability are reviewed.

I-5.1.2 Air masses, convergence zones, and wind systems

During the course of a year, Benin is alternatively affected by relatively cool and humid monsoon air mass originating from the Gulf of Guinea, and the hot, dry, and dusty Saharan air mass. The border between these two air masses is called the Inter-Tropical Front (ITF) (Hamilton and Archbold 1945). The ITF is located at the center of the continental surface heat low and is not associated with rainfall activity during a majority of the time. It must not be confused with the Inter-Tropical Convergence Zone (ITCZ). The ITCZ can be delineated on monthly rainfall maps by a nearly east-west oriented zone of maximum rainfall. This zone is located between 6° and 10° latitudes south of the ITF. It is the seasonal south-north migration of the ITCZ that determines the 'modality' of rainfall in West Africa (see sect. I-3.4).

The cooler air mass from the Gulf of Guinea is transported inland by the low-level monsoonal south-westerlies (see fig. I-5.1.1a). The monsoon winds are light winds with the highest near-surface wind speeds over the Gulf of Benin reaching about 6 m s^{-1} and speeds of only 3-4 m s^{-1} over the continent (see fig. I-5.1.1a). The monsoonal south-westerlies wedge under the hot Saharan north-easterly trades – the so-called Harmattan winds. As a result, a north-south temperature gradient with northward increasing temperature is found in the lower 4 km of the atmosphere in the ITF region (e.g., fig. 3 in Pytharoulis and Thorncroft 1999). The result of this temperature contrast is a westward blowing thermal wind – the so-called African Easterly Jet (AEJ; see fig. I-5.1.1b) – that reaches the maximum wind speed at a height of about 4 km,

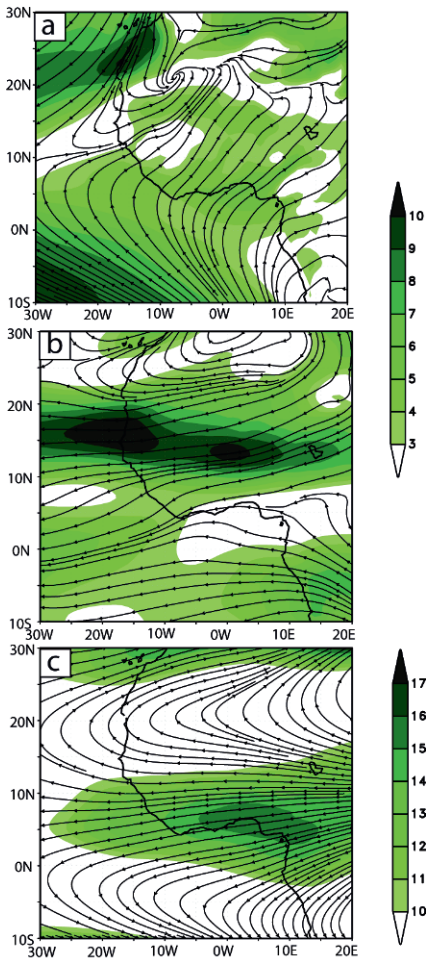

Fig. I-5.1.1: Streamlines and isotachs (shaded) in m s^{-1} at 925 (a), 700 (b), and 200 hPa (c) for the period June-September 1989-2008 based on the ERA-Interim reanalysis. Data are averaged over twice-daily analysis times at 00 and 12 UTC. Note the different shading of the isotachs at 200 hPa.

where the north-south temperature gradient reverses. At the peak of the summer monsoon, the surface ITF lies just north of 20°N (see fig. I-5.1.1a) and the AEJ is found at about 15°N with mean wind speeds in excess of 10 m s^{-1} (see fig. I-5.1.1b). At that time, a second stronger jet stream – the so-called Tropical Easterly Jet (TEJ, see fig. I-5.1.1c) –that reaches the maximum wind speed at a height of about 12–14 km blows along the Guinea coast. Mean wind speeds within the TEJ are greater than 15 m s^{-1}. The TEJ is largely a consequence of the upper-level pressure gradient between the high pressure over the Sahara and the lower pressure above the Gulf of Guinea (Fink 2006). The ITCZ (i.e., the maximum rainy zone) is zonally 'sandwiched' between the AEJ and the TEJ (Nicholson 2008). In the literature, rainfall anomalies in West Africa in general, and in Benin in particular, have often been associated with an unusual northward or southward position of the ITCZ and the associated low- and upper-level jet streams (e.g., Nicholson 2008). This explanation can clarify so-called 'dipole years' with opposite annual rainfall anomalies in the Sahel and the Guinea coast regions. Nicholson (2009) recently argued that during 'non-dipole years' (years when the entire West African continent shows negative or positive rainfall anomalies), the width of the rainbelt is determined by the latitudinal separation of the AEJ and TEJ axes; on the other hand, rainbelt intensity is, amongst other factors, related to the TEJ intensity and associated upper-level divergence anomalies. One important clue in establishing the as of yet unclear physical process link between the large-scale climate environment and the forcing of rainfall is a better understanding of the rainfall bearing weather types. Thus, one focus of meteorological research within IMPETUS has been on the understanding of 'West African rainfall types' and their characteristics, seasonal distribution, and contribution to the annual rainfall.

I-5.1.3 The seasonal cycle

Atmospheric circulation and disturbances

The atmospheric conditions above West Africa change continuously throughout the year. During the dry season between November and February, the central and northern regions of Benin are located north of the ITF and are thus under the influence of the dry and dusty Harmattan winds (Hamilton and Archbold 1945). Occasionally, the Harmattan winds surge towards the equator to reach the Guinea coast (Knippertz and Fink 2006a). The duration of Harmattan conditions in Benin for a given location vary substantially from year to year. For example, the 2005/2006 season experienced many more humid days than the 2006/2007 season (Pospichal 2009). Given the difference in potential evaporation over a water surface between more than 10 mm and less than 4 mm per day north and south of the ITF (see sect. I-3.4), the 2006/2007 Harmattan season likely experienced stronger

actual evapotranspiration than the preceding season. In addition, while some Harmattan seasons stay entirely dry, strong rainfall can sometimes occur during the dry season with a strong impact, ranging from damaging to cotton harvests stored under an open sky to beneficial for cattle nomads or the mango harvests (Knippertz and Fink 2009). These authors found that an average of two strong rainfall events occurred in the zone between 7.5° and 12.5°N during the dry seasons 1979/80 –2001/2002. In order to better understand the dynamics of dry season rainfall, Knippertz and Fink (2008) conducted a case study of a strong rainfall event that affected Benin in January 2004. They demonstrated that it was caused by an upper-level, extratropical low that penetrated from Northwest Africa into the West African tropics, causing the ITF to shift into an unusual northward position. In the wake of the poleward-shifting ITF, the warm and humid air mass from the Gulf of Guinea surged northward to cover the entire country of Benin. Strong daytime heating, present even during boreal winter, triggered numerous afternoon thunderstorms in this humid air mass. The same authors also point out that this type of tropical-extratropical interaction (TEI) is often visible in satellite images by an upper-level cloud band, a so-called Tropical Plume (TP). The TP occurs at the eastern flank of the upper-level low (Knippertz and Fink 2006b).

In March and April, increasing solar radiation over the Sahel and Sahara causes a strengthening and northward progression of the continental heat low and the ITF (fig. 4 in Lavayasse et al. 2009). Consequently, the relatively cool, moist, and convectively unstable monsoon air penetrates farther into the continent. During this pre-monsoon season, the depth of the monsoon layer increases and short-term northward excursions of the ITCZ generate the first substantial rainfalls in the Benin littoral. Farther northward in the Soudanian zone, the start of the rainy season is delayed until May or June (Le Barbé et al. 2002). The northward excursions of the ITCZ during the pre-monsoon season are still mostly associated with upper-level extratropical disturbances. It should be stressed that while rainfall-based monsoon onset criteria define the start of the monsoon season along the Beninese coast as early as March, the ‘dynamical onset’ of the monsoon does not occur until the third decade of June (Sultan und Janicot 2003; Sultan et al. 2003). Thus, the amount of rainfall during the pre-monsoon season from March through June is an unsuitable predictor of the quality of the summer monsoon; rainfalls during the pre- and regular monsoon seasons are triggered by different dynamic processes. Furthermore, extensive dry spells are observed during the pre-monsoon season that may cause significant crop losses in Benin.

Around the mean dynamical onset date of 24 June, the ITCZ abruptly jumps from 5°N to approximately 10°N, resulting in abundant rainfall and cloudy conditions in northern Benin. Preferably between June and September, the strong thunderstorm complexes in the entrance region of the AEJ in the Lake Chad region cause the AEJ to become unstable (Thorncroft et al. 2008), i.e. the east-west alignment of the AEJ changes into a wave pattern. These so-called African Easterly Waves (AEWs) are atmospheric disturbances in the easterly jet stream between 3–5 km, and propagate westward at about 25 km h^{-1}. The AEWs are the dominant

synoptic-scale features of the West African monsoon during the boreal summer (Carlson 1969a, b). Fink and Reiner (2003) have shown that AEWs likely trigger large thunderstorm complexes in the Guineo-Soudanian zone ahead of the wave trough, where winds at altitudes between 3 and 5 km change from easterly to north-easterly. They also show that this relation becomes stronger as the AEW amplitude increases from the Greenwich Meridian towards the West African coast. Thus, the role of AEWs for rainfall at the longitudes of Benin is somewhat limited. It should be emphasized that during the height of the monsoon season between June and September, an influence of the extratropics on the weather in tropical West Africa is generally rare. In addition, the littoral is affected by the 'little dry season' during this period; this little dry season is , among other reasons, related to the seasonal appearance of colder sea-surface temperatures along the Gold and Western Slave Coast, which inhibit convective rainfall (Vollmert et al. 2003).

The swift monsoon withdrawal toward the equator from September to November causes a second, less intense rainy season in the south (Fink et al. 2008). By the end of November, the ITCZ retreats southward over the equatorial Gulf of Guinea and the dry season sets in again over Benin.

Rainfall types

Annual statistics of individual rainfall producing weather systems account for the variability in the climatological rainfall amount in West Africa (Bell and Lamb 2006). Understanding the general characteristics and environmental atmospheric conditions favoring different rainfall types is thus crucial to understanding and modeling past and future rainfall variations. Rainfall over West Africa is mostly of convective nature, which means that potential vertical instability of the atmosphere is released and localized, but often heavy rainfall of short duration, is observed. A characteristic feature of the West African rainfall climate is that these isolated, mostly thundery showers organize into large thunderstorm complexes covering more than 5,000 km^2 and lasting for several hours. The generic term for these organized thunderstorm systems is Mesoscale Convective Systems (MCSs). In this subsection, we will elaborate on sub-types of MCSs and discuss their seasonal and daily frequency occurrences in Benin.

As mentioned at the beginning of this subsection, infrequent rainfall between November and March are caused by extratropical disturbances. These upper-level lows support the organization of afternoon thunderstorms into larger complexes. Contrary to rainfall systems during the summer monsoon, these extratropically-forced convective complexes do not propagate westward, but tend to show a northward movement (fig. 3 in Knippertz and Fink 2008). In the central and northern parts of Benin, some very light rainfall can occur underneath a TP. Beginning in March and lasting until November, the Benin littoral experiences substantial rainfall associated with the land-sea breeze circulation. Light convective showers cross the coastline during morning hours and then develop into strong afternoon thun-

dershowers while propagating inland. This local circulation cause a maximum likelihood of rainfall between 09 and 10 Local Time (LT, Universal Time Coordinated, UTC + 1 hour) at Cotonou and at about 18 LT at Bohicon in the diurnal cycle of rainfall (Fink et al. 2008). The land-sea breeze convection is most pronounced during March – May and October – November, outside the peak of the monsoon season. The land-sea breeze circulation causes an earlier start of rains after the dry season in the hinterland of the coast, as compared with the coast.

Between April and October, Benin is affected by intense westward propagating MCSs. The fast eastward-moving (> 36 km h^{-1}), large (≥ 5,000 km^2) MCSs were named Organized Convective Systems (OCSs) by Mathon et al. (2002). In central Benin, an OCS passage in the Haute Vallée de l'Ouémé (HVO) causes a typical distribution of rainfall intensities (see fig. I-5.1.2). In the leading convective part of the OCS, intense rainfall occurs with mean intensities of more than 20 mm h^{-1}, peaking at 100 mm h^{-1} for the most intense systems. The start of the intense rains is preceded by gusty winds that can reach hurricane strength. Figure I-5.1.3 displays the mean wind and maximum wind gusts at Gaya, which is located at the border between Benin and Niger. At Gaya, the 2005 season of the squally MCSs began in mid-April and lasted until early October. It is worth noting that a peak gust of 42.5 m s^{-1} corresponding to 153 km h^{-1} was recorded on 14 June 2005 at 16:30 UTC (see fig. I-5.1.3). Even though the event is an extreme example, such strong gusts occur more frequently during the pre-monsoon season and cause substantial local damage to buildings, trees and crop fields. Aside from pre-monsoonal dry spells, the flash floods and wind damage associated with the convective part of the MCS are of major concern to farmers in the HVO.

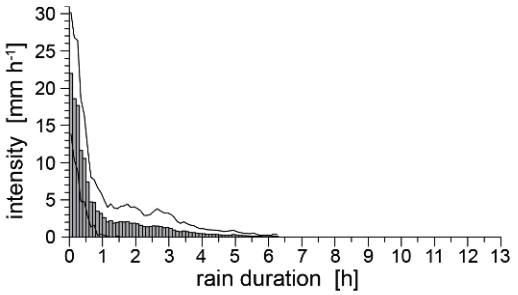

Fig. I-5.1.2: Composites of 6-minute rain rates versus rainfall duration averaged over all operating rain gauges in the *Haute Vallée de l'Ouémé* (HVO) in central Benin and all 52 OCSs during the 2002 rainy season. The two curves delineate the +/- one standard deviation range (Source: Fink et al. 2006b).

After the passage of the convective part of an OCS, there are usually light rainfalls with intensities of several mm h^{-1} that last for about 3–4 hours (see fig. I-5.1.2). This light rainfall is associated with the stratiform part of an OCS. Satellite microwave images reveal that the leading convective part of an OCS is often associated with a bow-shaped, curvilinear, north-south oriented line of intense thunderstorms (see fig. 3 in Fink and Reiner 2003). Thus, the majority of OCSs consist of what is often referred to in literature as a Squall Line (SL) system (Houze 1977). During the 2002 rainfall season, Fink et al. (2006b) tracked MCSs that caused rainfall in the HVO and found that OCSs contributed to about 56% of the total HVO rainfall that year. About 26% of annual rainfall was attributable to

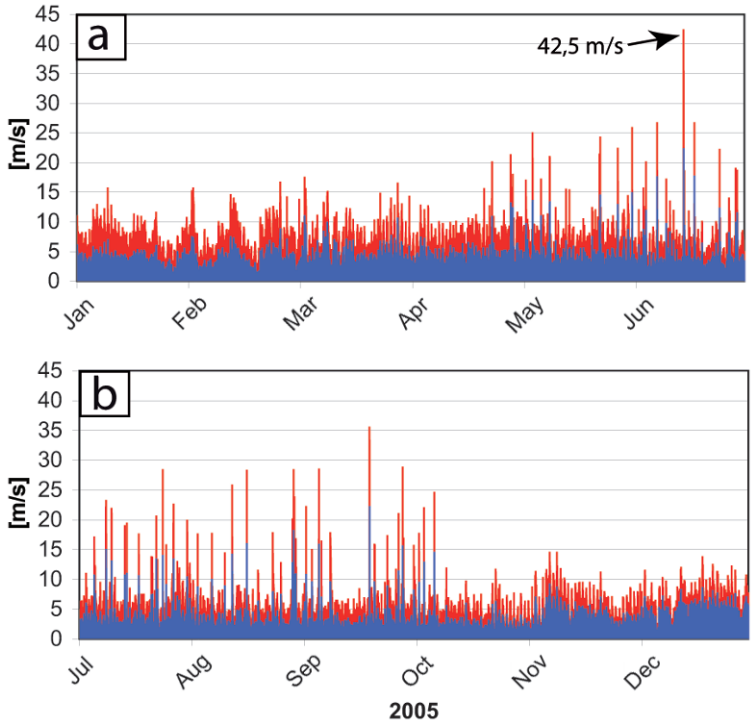

Fig. I-5.1.3: 10-minute mean (in blue) and maximum wind gusts (i.e., 1-second peak wind speed, in red) 10-metre wind speed in m s^{-1} at Gaya located in southern Niger (11°53′N; 3°27′E) for 2005. The arrow indicates the extreme wind gust of 153 km h^{-1} on 14 June 2005 16:30 UTC.

slower-moving MCSs that failed to reach the 'greater than 36 km h^{-1}' propagation speed criterion of OCSs. These MCSs were generally shorter-lived, less extensive in area, and occurred most frequently during the height of monsoon season. These characteristics are the consequence of an atmosphere that is moist and exhibits only small wind changes with height during this time of year (Fink et al. 2006b). The OCSs and MCSs often developed far east of the HVO over the central Nigerian highlands (see fig. 5 in Fink et al. 2006b) and arrived over the HVO after midnight, causing the likelihood of rainfall at Parakou to be greatest between 02 and 04 LT (Fink et al. 2008). In 2002, the primary peak of accumulated rainfall for the HVO occurred between 18 and 24 UTC, stemming from OCSs and MCSs that are either formed in the vicinity of the HVO along the Niger valley or over the Oshogbo Hills in southwest Nigeria (see fig. 6 in Fink et al. 2006b).

Two other rainfall types remain to be discussed. The first type is monsoon rains characterized by prolonged periods of steady or intermittent, light to moderate rainfall from rainstorms with a low electrical activity. They develop when the low change of wind speed and direction with height prevents convective organiza-

tion. There appears to be no commonly accepted definition of this rainfall type (Fink et al. 2006b and references therein). Fink et al. (2006b) found a class of rainfall events occurring in a peculiar synoptic situation, during which a low- to mid-level disturbance led to deep (at least 3 km) westerly flow in the HVO region. These 'vortex-type' rainfalls contributed to 9% of annual rainfall in the HVO and may be similar to monsoon rains. The second type of rainfall is local instability showers, which are typical for the wet season over the entire West African subcontinent (Kamara 1986). These nearly stationary rainstorms are localized (20–50 km2) and often thundery in nature, with a typical lifetime of 1 to 2 h (Kamara 1986). They are generated more frequently during afternoon hours when atmospheric ground levels are heated by the sun's insulation. Aside from the primary, OCS-related peak after midnight, they cause a secondary peak in rainfall probability in the afternoon, which can be observed, for example, at Natitingou in the Beninese Atacora Mountains. The instability showers contributed about 5% to annual rainfall in the HVO in 2002. The contributions by different rainfall types to the 2002 rainfall total are summarized in table I-5.1.1.

Table I-5.1.1: The contributions of the different types of rainfall to the annual total of 2002 [in %].

OCSs	Slow MCSs	Vortex-type rainfall	Instability showers	Unclassified
56	26	9	5	4

I-5.1.4 Interannual-to-decadal rainfall variability

The monthly and yearly rainfall totals for 1921–2005 are displayed in figure I-4.2.2 for northern Benin, the HVO, and the Lower and Middle Ouémé valley. When compared with the Standardized Precipitation Index (SPI) rainfall time series for the Central Sahel and the Guinea coast (see fig. I-3.4.2b), it is evident that the Ouémé regions and northern Benin exhibit, not surprisingly, a similar interannual rainfall variability than the Guinea coast rainfall index. Note that rainfall data from Cotonou and Parakou have entered the calculation of the Guinea coast rainfall index. However, the northern region (and the HVO region, to a lesser extent) exhibits a strong coherence with rainfall anomalies of the Sahel on decadal time scales. With respect to long-term variability, dryer conditions during the 1940s and wetness during the 1960s are noteworthy, with 1964 and 1968 being the wettest years recorded in the littoral. The dry decades of the 1970s and 1980s were most pronounced in northern Benin. All regions in Benin exhibited some recovery of rainfall in recent years (see fig. I-4.2.2).

Figure I-5.1.4 shows the long-term variability in the number of days with rain in excess of 1 and 40 mm for the same three regions in Benin. Two features of

this figure are noteworthy. First, the dryness during the 1970s and 1980s was due to both the reduction in rainy days and the number of strong events in all regions. On the other hand, the drier 1940s in northern Benin seem primarily caused by a decreased frequency of strong events occurrences. This has also been observed at Niamey during a drought in the 1970s and 1980s (Shinoda et al. 1999). Second, recent rainfall recovery in northern Benin is apparently related to an increase in the number of strong events. These observations corroborate the earlier notion that the knowledge of rainfall types and their contribution to annual rainfall is indispensable for the understanding of temporal rainfall variability in Benin. Consistent with a larger variety of rainfall types in southern Benin (i.e., OCSs, vortex-type rainfall, land-sea breeze circulation, and instability shower), changes in the number of rainy days seem as important as changes in the frequency of occurrence of strong rainfall events. In contrast, changes in the number of OCSs per year in northern Benin (OCSs often cause more than 20 mm daily rainfall and the bulk of the annual rainfall in northern Benin) determine the low-frequency rainfall variability. Changes in the monsoon onset and withdrawal between the Climate Normal periods 1931-1960 and 1961-1990 have been investigated. The latter drier period was associated with a somewhat later monsoon onset in Central Benin by about a week; it was also associated with an earlier withdrawal of the second rainy season all over Benin with the largest values of about two weeks in the littoral. The latter behavior has also been noted by Le Barbé et al. (2002). Temperature trend maps obtained from the gridded CRU (Climate Research Unit) data set yield a positive trend in the annual mean temperature of more than 1°C in

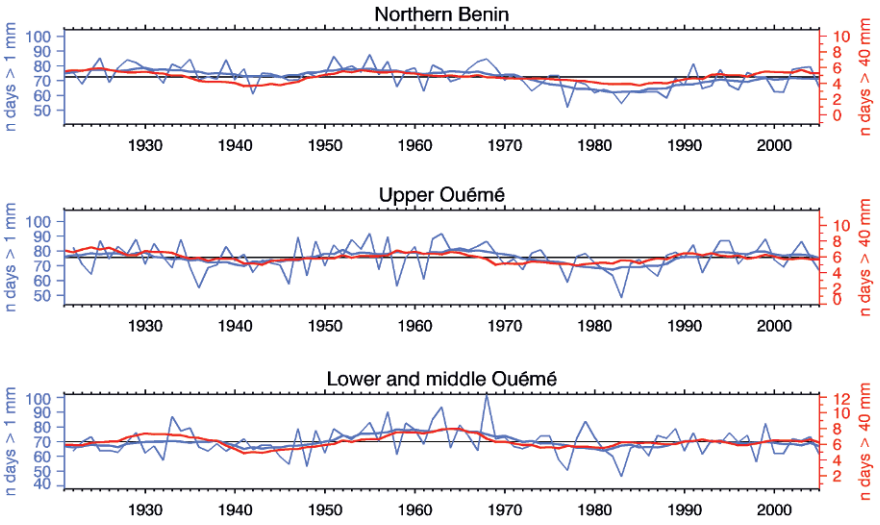

Fig. I-5.1.4: Number of rainy days per year (thin blue line, bold blue line: 11-year running mean) and 11-year running mean of days with over 40 mm of precipitation per year measured by stations in three regions of Benin (fig. I-4.2.1a). The black line indicates the mean of 1921–2005 (Source: Diederich and Simmer 2008).

the north of Benin between 1960 and 1998. There is no or even a negative temperature trend in the Benin littoral.

I-5.1.5 The role of sea surface temperatures in West African rainfall

The oceanic boundary condition in the tropical Atlantic is likely to impact West African summer monsoon rainfall because the rain-bearing monsoonal southwesterlies are enriched by moisture over this region before penetrating the West African subcontinent (see fig. I-5.1.1a). The rainfall response to sea surface temperatures (SSTs) is not spatially homogeneous: along the Guinea coast, warmer SSTs lead to increased rainfall amounts during boreal summer (Ruiz-Barradas et al. 2000), while the Sahel zone is usually affected by dryer conditions (Mo et al. 2001; Paeth and Stuck 2004). Vizy and Cook (2001) have explained this dipole structure with an atmospheric wave response to tropical oceanic heating that basically suppresses rainfall over the Sahel by inducing negative vertical motion anomalies at upper levels (Paeth and Hense 2006). The ITCZ location over West Africa is also related to an interhemispheric SST gradient in the Atlantic Ocean, with a warmer North Atlantic attracting the ITCZ towards a more northward position (Ward 1998). In addition, there is a teleconnection to the tropical Pacific: El Niño events are often accompanied by less (more) rainfall along the Guinea coast (Sahel zone) (Janicot et al. 2001). Finally, a decadal increase of SSTs in the Indian Ocean seems to reduce West African rainfall, particularly in the Sahelian belt (Bader and Latif 2003). Rowell (2003) points to the enhancement of Sahel rainfall when the eastern Mediterranean Sea is warmer than normal.

These studies rely primarily on observational data that are subject to a variety of competing influences. In order to detect and quantify the SST forcing of the West African monsoon system, various atmospheric climate model experiments driven by observed SSTs in the 20th century have been carried out since the 1990s (Palmer et al. 1992; Sutton et al. 2000; Giannini et al. 2003; Paeth and Hense 2004). These model studies support the hypothesis that SST changes play a prominent role in low-frequency variations of West African summer monsoon rainfall. The time series in figure I-5.1.5a and figure I-5.1.5b reveal that SST-driven experiments with the ECHAM4 and HadAM2 atmospheric climate models reproduce the observed decadal trend of rainfall observed at the Guinea coast and the Sahel between the 1960s and 1990s. Although the amplitudes are systematically underestimated by the models, this finding clearly indicates that SST changes have contributed to the drought occurrence in sub-Saharan West Africa.

Given an ensemble of climate model simulations with identical SST forcing and different initial conditions, the relative importance of SST changes to total rainfall variability can be quantified by a decomposition of the total variance. The classical statistical tool is the analysis of variance (ANOVA), which is used to separate the forced variations from internal variability (Paeth and Hense 2002). Fig-

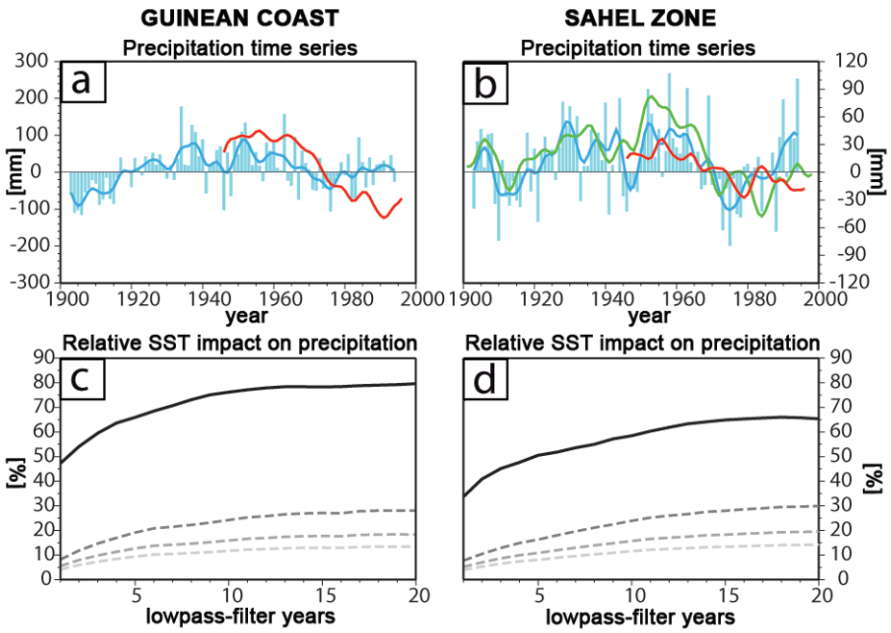

Fig. I-5.1.5: Time series of 9-year low-pass filtered regional-mean annual rainfall departures from the 1961-1990 mean along the Guinea Coast (a) and in the Sahel zone (b) as simulated by SST-forced atmospheric climate model simulations with the ECHAM4 model (blue line) and the HADAM2 model (red line) as well as observed (green line). The blue bars indicate the ECHAM4 simulated annual values. Relative impact of SST changes, expressed as the percent variance explained by SST of the total interannual rainfall variability in an ensemble of ECHAM4 simulations at different scales of low-pass filtering along the Guinea Coast (c) and in the Sahel (d). The dashed lines denote the 10%, 5% and 1% confidence levels, respectively.

ures I-5.1.5c and I-5.1.5d arise from a spectral application of the ANOVA; progressive low-pass filters between 1 and 20 years have been applied prior to the decomposition of the total variance. The objective is to assess the prominent temporal scales of rainfall variability, which are dominated by the SST forcing. The spectra demonstrate that the influence of SST prevails mainly at the decadal time scale (10–15 years). Along the Guinea coast, SST changes explain 50% of the interannual rainfall fluctuations and dominate the decadal and interdecadal variations by almost 80% (see fig. I-5.1.5c). The SST impact is weaker in the Sahel zone: around 40% of total rainfall variability is explained at the interannual time scale, while 65% are exceeded at the scale of 15–20 years (see fig. I-5.1.5d). This difference is easily explained by the larger distance to oceanic moisture sources in the tropical Atlantic. In a systematic multivariate analysis, Paeth and Friederichs (2004) compared tropical oceanic basins and found that the SST-rainfall link in West Africa is composed of manifold teleconnections with the Atlantic, Pacific and Indian Oceans, with the closest relationship to the tropical Atlantic. In sum-

mary, there is a large potential in predicting seasonal rainfall anomalies especially along the Guinea coast. Hitherto, this potential has not been exploited due to the inability of coupled ocean-atmosphere forecast models to predict the changes of SSTs in the Gulf of Guinea region during boreal summer.

The systematic underestimation of observed variability may be due to the missing interaction with vegetation cover and land surface processes in climate model simulations (Pielke 2001; Schnitzler et al. 2001; Zeng et al. 2002). Model sensitivity studies performed within IMPETUS by Sogalla et al. (2006) suggest that even land use changes on the scale of the HVO may impact the local rainfall distribution.

I-5.1.6 The role of greenhouse gases and aerosols in West African rainfall

The majority of existing model experiments predict more humid conditions in the Guinea coast region, whereas drought anomalies prevail in the Sahel when greenhouse gas (GHG) concentrations continue to increase (Paeth and Hense 2004; IPCC 2007). In addition, the African continent appears to be a paradigm for the climate forcing by aerosols – mineral dust is predominantly produced in the Sahara, but aerosol concentrations from biomass burning – especially black carbon and particulate organic matter – show a peak over tropical Africa (Stier et al. 2004). In this region human activity governs fire occurrence since the beginning of the Holocene with nowadays unprecedented frequency and spatial extent (Bird and Cali 1998). Sensitivity studies with the global climate model ECHAM4/HAM – a general circulation model combined with a sophisticated aerosol model – investigate the effects of present-day versus preindustrial concentrations of GHGs and aerosols, and suggest opposite impacts on African rainfall (Paeth and Feichter 2006). While enhanced greenhouse forcing produces more rainfall in the southern region of West Africa, increased aerosol concentrations are accompanying drier conditions in the West African monsoon region. Rotstayn and Lohmann (2002) have described a dynamical mechanism of how aerosol may affect the interhemispheric SST gradient in the Atlantic Ocean, involving extratropical aerosol emissions and processes. The interhemispheric SST gradient is a main player in West African rainfall anomalies by altering the large-scale atmospheric circulation and the spatial extent of the Azores High (Ward 1998). The Atlantic SST dipole is modified towards a stronger cooling in the North Atlantic than in the Southern Hemisphere counterpart because aerosol effects prevail mainly during the boreal summer, when the incoming solar radiation and atmospheric aerosol burden over the Northern Hemisphere are enhanced. This interhemispheric SST anomaly pattern is usually associated with a southward displacement of the ITCZ, dryer than normal conditions in sub-Saharan West Africa and weaker summer monsoon circulations. In summary, it is believed that mostly natural SST variations in the tropical ocean basins accounted for the recent decadal rainfall fluctuations in tropical West Africa.

Some modeling work indicates a contribution of the aerosol loading to the Sahel drought at the end of the last century.

I-5.1.7 Conclusions

Atmospheric, land surface, and oceanic processes in the West African monsoon region are very complex. As of yet, the chain of processes that link, for example, worldwide anomalies of upper-layer ocean temperatures with rainfall in the Sahel and Guineo-Soudanian zones are not fully understood. These teleconnections are also non-stationary, i.e. they vary over time scales of decades. From the more regional Beninese perspective, meteorological research within IMPETUS has elucidated the different types of rainfall that occur under the seasonal-varying meteorological conditions in the country. From the impact perspective, a particular relevant and unexpected finding for day-to-day weather forecasting operations is the realization that advanced warnings of heavy dry-season rainfall events seem to be possible due to their good predictability on multi-day time scales (Knippertz and Fink 2009). At the seasonal time scale, the investigations within IMPETUS underpinned the large potential for seasonal forecast in Benin using predicted SSTs, especially in the Atlantic Ocean including the Gulf of Guinea (Paeth and Friedrichs 2004). At present, an exploitation of this potential is hampered by the low skill of predicting the SSTs in the Gulf of Guinea. For climate projections, the process and modeling studies within IMPETUS strongly suggested the inclusion of the effects of land use changes in climate projections. How this has been achieved and what the consequences were is described in section II-3.2.

References

Bader J, Latif M (2003) The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation. Geophys Res Lett 30. doi:10.1029/2003GL018426

Bird MI, Cali JA (1998) A million-year record of fire in sub-Saharan Africa. Nature 394:767-769

Bell MA, Lamb PJ (2006) Integration of weather system variability to multidecadal regional climate change: The West African Sudan-Sahel zone, 1951-98. J Climate 19:5343-5365. doi:10.1175/ JCLI4020.1

Carlson TN (1969a) Synoptic histories of three African disturbances that developed into Atlantic hurricanes. Mon Weather Rev 97:256-276

Carlson TN (1969b) Some remarks on African disturbances and their progress over the tropical Atlantic. Mon Weather Rev 97:716-726

Fink AH, Reiner A (2003) Spatio-temporal Variability of the Relation between African Easterly Waves and West African Squall Lines in 1998 and 1999. J Geophys Res-Atmos. doi:10.1029/2002JD002816

Fink AH (2006) The West African monsoon system. Promet 32:114-122

Fink AH, Vincent DG, Ermert V (2006) Rainfall Types in the West African Soudanian Zone during the Summer Monsoon 2002. Mon Weather Rev 134:2143-2164

Fink AH, Kotthaus S, Pohle S (2008) Rainfall Variability in West Africa. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 21-22. Department of Geography, University of Bonn, Bonn

Giannini A, Saravanan R, Chang P (2003) Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. Science 302:1027-1030

Hamilton RA, Archbold JW (1945) Meteorology of Nigeria and adjacent territories. Q J Roy Meteor Soc 71:231-265

Houze RA Jr (1977) Structure and Dynamics of a Tropical Squall-Line System. Mon Weather Rev 105:1540-1567

IPCC (2007) Climate Change 2007: The Physical Science Basis. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Janicot S, Trzaska S, Poccard I (2001) Summer Sahel-ENSO teleconnection and decadal time scale SST variations. Clim Dynam 18:303-320

Kamara I (1986) The origins and types of rainfall in West Africa. Weather 41:48-56

Knippertz P, Fink AH (2006a) Synoptic and Dynamic Aspects of an Extreme Springtime Saharan Dust Outbreak. Q J Roy Meteor Soc 132:1153-1177

Knippertz P, Fink AH (2006b) Tropical plumes: A visible sign of tropical–extratropical interactions. Promet 32:144-153

Knippertz P, Fink AH (2008) Dry-Season Precipitation in Tropical West Africa and its Relation to Forcing from the Extratropics. Mon Weather Rev 136:3579-3596

Knippertz P, Fink AH (2009) Prediction of Dry-Season Precipitation in Tropical West Africa and its Relation to Forcing from the Extratropics. Weather Forecast 24(4):1064-1084

Lavayasse C, Flamant C, Janicot S, Parker D J, Lafore JP, Sultan B, Pelon P (2009) Seasonal evolution of the West African Heat Low: A climatological perspective. Clim Dynam 33:313-330

Le Barbé L, Lebel T, Tapsoba G (2002) Rainfall Variability in West Africa during the Years 1950-90. J Climate 15:187-202

Mathon V, Laurent H, Lebel T (2002) Mesoscale convective system rainfall in the Sahel. J Appl Meteorol 41:1081-1092

Mo K, Bell GD, Thiaw MW (2001) Impact of sea surface temperature anomalies on the Atlantic tropical storm activity and West African rainfall. J Atmos Sci 58:3477-3496

Nicholson SE (2001) Climatic and enviromental change in Africa during the last two centuries. Clim Res 17:123-144

Nicholson SE (2008) The intensity, location and structure of the tropical rainbelt over west Africa as factors in interannual variability. Int J Climatol 28:1775-1785

Nicholson SE (2009) On the factors modulating the intensity of the tropical rainbelt over West Africa. Int J Climatol 29:673-689

Paeth H, Feichter J (2006) Greenhouse-gas versus aerosol forcing and African climate response. Clim Dynam 26:35-54

Paeth H, Friederichs P (2004) Seasonality and time scales in the relationship between global SST and African rainfall. Clim Dynam 23:815-837

Paeth H, Hense A (2002) Sensitivity of climate change signals deduced from multi-model Monte Carlo experiments. Clim Res 22:189-204

Paeth H, Hense A (2004) SST versus climate change signals in West African rainfall: 20th century variations and future projections. Climatic Change 65:179-208

Paeth H, Hense A (2006) On the linear response of tropical African climate to SST changes deduced from regional climate model simulations. Theor Appl Climatol 83:1-19

Paeth H, Stuck J (2004) The West African dipole in rainfall and its forcing mechanisms in global and regional climate models. Mausam 55:561-582

Palmer T, Brankovic C, Viterbo P, Miller MJ (1992) Modelling interannual variations of summer monsoons. J Climate 5:399-417

Pielke RA (2001) Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. Rev Geophys 39:151-177

Pospichal, Bernhard (2009): Diurnal to annual variability of the atmospheric boundary layer over West Africa: A comprehensive view by remote sensing observations. Doctoral thesis at the Department ("Fakultät") of Mathematics and Natural Sciences of the University of Cologne. 120 pp., online available at: http://kups.ub.uni-koeln.de/volltexte/2010/2985/pdf/dissertation_pospichal.pdf

Pytharoulis I, Thorncroft C (1999) The Low-Level Structure of African Easterly Waves in 1995. Mon Weather Rev 127:2266-2280

Rotstayn LD, Lohmann U (2002) Tropical rainfall trends and the indirect aerosol effect. J Climate 15:2103-2116

Rowell DP (2003) The impact of Mediterraenean SSTs on the Sahelian rainfall season. J Climate 16:849-862

Ruiz-Barradas A, Carton JA, Nigam S (2000) Structure of interannual-to-decadal climate variability in the tropical Atlantic sector. J Climate 13:3285-3297

Schnitzler K-G, Knorr W, Latif M, Bader J, Zeng N (2001) Vegetation feedback on Sahelian rainfall variability in a coupled climate land-vegetation model. Max-Planck-Institute for Meteorology, Report No. 329

Shinoda M, Okatani T, Saloum M (1999) Diurnal variations of rainfall over Niger in the West African Sahel: A comparison between wet and drought years. J Climatol 19:81-94

Sogalla M, Krüger A, Kerschgens M (2006) Mesoscale modelling of interactions between rainfall and the land surface in West Africa. Meteorol Atmos Phys 91: 211-221

Stier P, Feichter J, Kinne S, Kloster S, Vignati E, Wilson J, Ganzeveld L, Tegen I, Werner M, Balkanski Y, Schulz M, Boucher O (2004) The aerosol-climate model ECHAM5-HAM. Atmos Chem Phys 4:5551-5623

Sultan B, Janicot S (2003) The West African Monsoon Dynamics. Part I: Documentation of Intraseasonal Variability. J Climate 16:3389-3406

Sultan B, Janicot S, Diedhiou A (2003) The West African Monsoon Dynamics. Part II: The „Preonset" and „Onset" of the Summer Monsoon. J Climate 16:3407-3427

Sutton RT, Jewson SP, Rowell DP (2000) The elements of climate variability in the tropical Atlantic region. J Climate 13:3261-3284

Thorncroft CD, Hall NM, Kiladis GN (2008) Three-Dimensional Structure and Dynamics of African Easterly Waves. Part III: Genesis. J Atmos Sci 65:3596-3607

Vizy EK, Cook KH (2001) Mechanisms by which Gulf of Guinea and Eastern North Atlantic sea surface temperature anomalies can influence African rainfall. J Climate 14:795-821

Vollmert P, Fink AH, Besler H (2003) "Ghana Dry Zone" und "Dahomey Gap": Ursachen für eine Niederschlagsanomalie im tropischen Westafrika (in German). Erde 134:375-393

Ward MN (1998) Diagnosis and short-lead time prediction of summer rainfall in tropical North Africa at interannual and multi-decadal time scales. J Climate 11:3167-3191

Zeng N, Hales K, Neelin JD (2002) Nonlinear dynamics in a coupled vegetation-atmosphere system and implications for desert-forest gradient. J Climate 15:3474-3487

I-5.2 Meteorological processes influencing the weather and climate of Morocco

K. Born, A. H. Fink, and P. Knippertz

Abstract

This section contains a description of rainfall variability in Morocco and the Drâa catchment. Long-term behavior of three regional Standardized Precipitation Indices (SPI) and the teleconnection to the North Atlantic Oscillation (NAO) and the El Niño/Southern Oscillation (ENSO) are discussed. The relation between Lamb's circulation weather types (CWT) and these indices is shown. The second section examines summer rainfall events in the Atlas Mountains, which are often initiated by tropical-extratropical interactions (TEI). Summer rainfall is typically in the form of thunderstorms or showers. During these events, the evaporation of raindrops in the dry near-surface air generates cold-air outflows from the mountain areas towards the south. These density currents raise dust, and in some cases also cause thunderstorms to develop over the desert.

Key words: Azores High, Circulation Weather Types, North Atlantic Oscillation, El Niño-Southern Oscillation, ENSO index, Icelandic Low, multiple regression, NAO index, sea-level pressure, sea surface temperature, seasonal prediction, Standardized Precipitation Index, teleconnection, tropical-extratropical interaction, precipitation variability, deep moist convection, moisture transport, upper-level troughs, cold pool, density current, dust, planetary boundary layer, evaporation, rainy season

I-5.2.1 Introduction

The Moroccan Drâa river catchment is located at the northern border of the northern-hemispheric subtropics, between the High Atlas Mountains in the north and the Sahara desert in the south. This location makes its environment unique; a wide range of climates prevails in the catchment, from nearly sub-humid mountain climates to desert climates at the northern Sahara boundary. Due to this environment, water is always a limiting factor for development in the region. In order to determine the causes and relationships of precipitation variability, the origin and occurrence of rainfall-bearing systems and their relation to global climate variability are discussed in this section.

Morocco has a winter rainy season, dry summers and strong interannual precipitation variability. The month of October marks the beginning of the rainy season, which lasts until April. Some characteristics of rainfall variability have already been discussed in section I-3.4. Looking at the spatial variation of the mean annual cycle, it is evident that an unimodal annual distribution of rainfall with maximum values in winter and spring prevails in the northern part of Morocco and the High Atlas Mountains, whereas there is no definite maximum in the southern parts (Born et al. 2008). Annual mean rainfall sums range from 600 mm in the northwestern part of Morocco to 50 mm or less at the Sahara border (see fig. I-3.4.1a). Mountain areas like the Rif receive more than 1000 mm of rainfall in some regions. Maximum rainfall in the High Atlas Mountains is hardly known because of a lack of long-term observations in that region. However, it can be assumed from older sources and observations from shorter time periods (see sect. I-4.3) that annual rainfall in the High Atlas Mountains may reach up to 800 mm.

Two aspects of rainfall variability are discussed in this section: the connection between precipitation and global climate variability, and the characteristics of orographically forced thunderstorms in the summer.

I-5.2.2 Winter precipitation in Morocco: How is Moroccan rainfall connected to global scale climate variability?

Climatic observations in Morocco

Only few data sets for Moroccan climate analysis are accessible. Direct observations of rainfall are collected in the Global Historical Climatology Network (GHCN) and were originally provided by the Office of Climatology at Arizona State University (Vose et al. 1992). Knippertz et al. (2003a) already utilized the GHCN data for the analysis of Moroccan rainfall variability; it has been extended by the IMPETUS project to cover the 1841–2007 period. A gridded data set of the interpolated historical climate data (provided by the Climate Research Unit (CRU), of the University of East Anglia and generally referred to as CRU TS2.1, Mitchell and Jones 2005) is used to evaluate climate data derived from GHCN. For an analysis of rainfall variability, standardized rainfall indices are usually studied rather than rainfall sums (Knippertz et al. 2003c; Bordi et al. 2006; Born et al. 2008). This is necessary to overcome problems of statistical analysis arising from the strong spatial heterogeneity of rainfall sums. The Standardized Precipitation Index (SPI; Born et al. 2008) is shown in figure I-5.2.1 as calculated from GHCN and from CRU TS2.1. (For the definition of the regions marked as ATL (Atlantic region), MED (Mediterranean coastal region) and SOA (south of the Atlas Mountains), see sect. I-3.4.) It is obvious that data before 1930 is not reliable and that the quality of data in the southern region becomes worse for a period during the

1960s; correlation between CRU and GHCN data reveals a lack of agreement between the datasets (see fig. I-5.2.1, right panels). For an analysis of weather types, the reanalysis data from National Centers for Environmental Prediction (NCEP); Kalnay et al. 1996) is used. Indices of the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO) are maintained and provided by CRU (Troup 1965; Jones et al. 1997; Osborn 2006).

Rainfall bearing weather situations and global climate variability

The sources of rainfall in northwestern Maghreb can be roughly classified into three categories: precipitation from weather systems connected with extratropical activity, tropical-extratropical interactions (TEI), and – especially in the mountain area – local thunderstorms caused by orographic forcing. The following teleconnections between global climate variability and Moroccan rainfall are of relevance: The first category of mid-latitude weather activity is connected with varia-

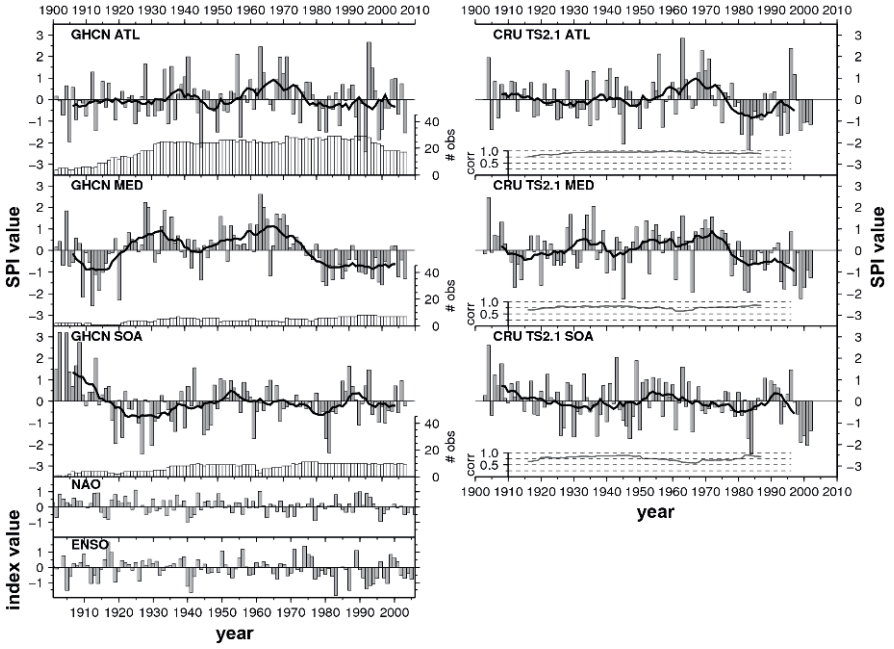

Fig. I-5.2.1: Left panels: Time series of annual SPI values obtained from GHCN station data for the period 1901/2–2006/7 for the ATL, MED, and SOA regions (see section I-3.4 and text below). Grey bars indicate SPI values for the hydrological years (Sep–Aug), the black line shows the 9yr-filtered values. White bars: number of available stations for each region. Bottom: NAO and ENSO indices time series provided by CRU (Osborn 2006). Right panels: The same for the CRU TS2.1 data, instead of numbers of stations the correlation in a moving 30-yr window are shown at the bottom.

bility in the North Atlantic Oscillation (NAO); the TEI events are possibly related to El Niño-Southern Oscillation (ENSO) via activity of tropical convection and associated moisture transports. The third category, locally-forced rainfall events, appear to be only weakly connected to larger scale conditions. This final type of rainfall often occurs in summer months and is discussed in detail in subsection I-5.2.3.

In the mid-latitudes, weather conditions are often connected to characteristics of westerly flow. For the northern Atlantic, its variability is commonly controlled by the NAO. A comprehensive description, also with respect to Morocco, is given in Lamb and Peppler (1987), and Lamb et al. (1997). Zonality of the prevailing flow over the North Atlantic can be described by an appropriate NAO index. One measure for the NAO is the pressure difference between the Icelandic Low and the Azores High: this measurement is used for the CRU NAO index by Jones et al. (1997), which represents normalized differences of surface pressure observations in southwest Iceland and Gibraltar. A high NAO index represents a strong zonal flow from the Atlantic towards Europe and advection of moist maritime air, which is often connected with wetter than normal conditions in Europe. Low NAO index values represent a meandering flow and allow for transport of cool and moist air into subtropical regions.

The ENSO phenomenon is connected with large-scale sea surface temperature (SST) anomalies in the tropical Pacific. A warm event with above-normal SSTs in the central and eastern Pacific, along with enhanced tropical convection in this region, cause the atmospheric, tropical, east-west oriented Walker circulation to be rearranged, thereby also affecting weather in the tropical Indian and the Atlantic Oceans. As a consequence, ENSO variability shows a teleconnection to rainfall variability in many tropical and subtropical regions of the world. The ENSO impact on tropical convection may also alter extratropical teleconnections and affect Morocco. It should be noted that ENSO teleconnections are primarily of statistical nature, and a physical relationship between ENSO and rainfall variability in other parts of the world remains elusive. An overview of ENSO and related climate variability can be found in Trenberth et al. (2002).

In order to provide an objective classification of typical weather conditions in Morocco, results of an analysis of weather types from sea-level pressure (SLP) values described in Knippertz et al. (2003a) are used. This analysis distinguishes different weather situations based solely on dynamical criteria of near-surface flow direction and curvature. The weather situations are categorized into so-called Circulation Weather Types (CWT; Jones et al. 1993). For our purposes, the classification scheme adapted by Pinto (2002) contains eight directional classes (NE, E, SE, S, SW, W, N W, and N) and two non-directional classes: local cyclonic (CYC), and anti-cyclonic circulations (AC). The scheme has been applied to NCEP SLP data for the 1960–2006 period. The typical SLP patterns connected with the CWT classes are shown in figure I-5.2.2, which shows that positions of the Azores High and extratropical depressions determine the flow direction in Morocco. For the C (AC) class, a low (high) pressure system is located over the Atlas.

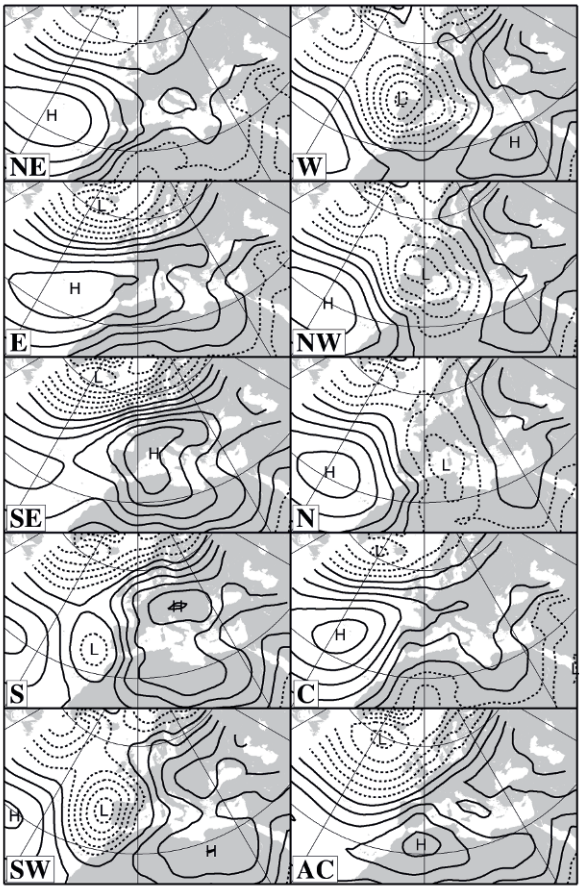

Fig. I-5.2.2: Typical SLP patterns connected with the 10 used CWT classes based on an analysis centered on 30°N and 5°W.

Figure I-5.2.3 depicts the mean annual cycle of the frequencies of CWT occurrences. The most prominent result is that two directional classes (NE and E) represent 40–80% of weather situations, and that the anticyclonic class (AC) is primarily present during winter months. The classes, for which the SLP patterns are shown in figure I-5.2.2, can be described as follows: The NE class is connected with strong Azores High and Icelandic Low. Due to the location of Morocco just outside the region influenced by the Azores High, conditions are more indefinite and a connection to rainfall in Morocco is not expected. The E class results from an easterly shifted Azores High and is usually connected with dry periods. The SE and S classes are connected with high pressures over Europe. For the SE class, the southerly flow transports dry air from the Sahara. For the S class, an accompanying low over the Canary Islands may lead to moist air advection and TEI. For the SW class, the trough offshore the Moroccan Atlantic coast is very strong and will often be connected with rainfall, especially in the south of Morocco. The W and NW classes are connected with depressions over Spain and will lead to rainfall mainly in the northern region. The N class is again connected with a strong Azores high and has less clearly determined consequences for rainfall. The cyclonic class C results from a cyclone over the High Atlas Mountains and bears rain on most of Morocco, with stronger influence on the southern parts. The anticyclonic AC class is connected with strong zonal flow over the Atlantic and shows no clear influence on Moroccan rainfall.

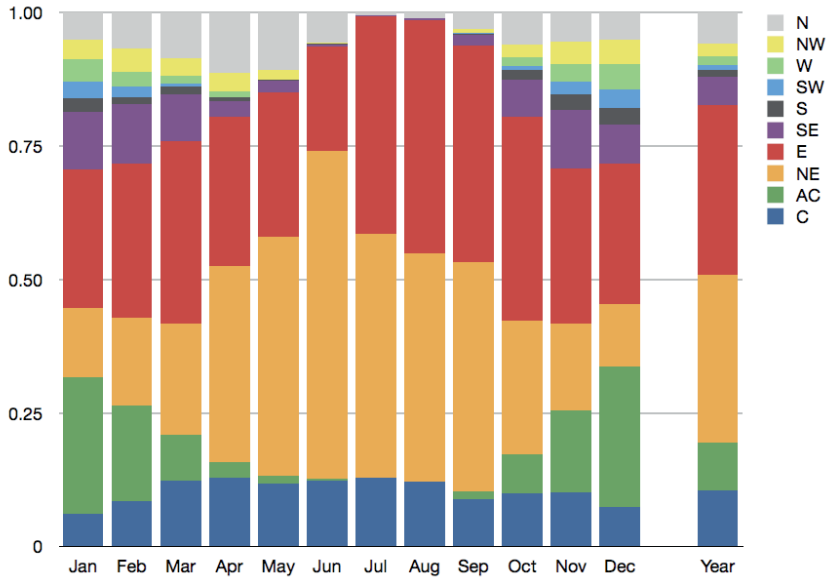

Fig. I-5.2.3: Annual cycle of CWT occurrences, as obtained from analysis of NCEP reanalysis data for the period 1960–2006 and for 30°N and 5°W.

The occurrence of typical weather situations in terms of atmospheric flow direction has become clearer through this analysis, but the connection to rainfall still needs to be examined. Since rainfall is very heterogeneous in space, we decided to analyze the SPI (see McKee et al. 1993; Born et al. 2008; and sect. I-3.4). The SPI is the transformation of the usually heavily skewed rainfall anomaly distribution into an almost normally distributed data set. The procedure of SPI calculation is as follows. Parameters of a theoretical distribution – in the present case, a Gamma distribution – are estimated from rainfall sums. Thus, for each value in the rainfall time series, we can assign a value to the cumulative probability of the theoretical distribution. The inversion of the cumulative standard normal distribution (error function) for this value is the SPI. Besides the spatial homogenization, another advantage of using SPI is the ability to compare different sources of data, such as climate model and observational data. For Morocco, an analysis of Empirical Orthogonal Functions (EOFs) shows that Morocco can be separated into three regions of similar rainfall variability (Knippertz et al. 2003a; Born et al. 2008). Figure I-3.4.2a shows the three regions: the northwestern coastal ATL region, the MED coastal region the SOA region. The corresponding SPI series in figure I-5.2.1 reveals a strong decadal variability, especially in the MED region, where a large negative anomaly has been observed since the 1980s. The following discussion presents two kinds of analyses. The relation between SPI and CWT occurrences connects rainfall anomalies to single CWT classes. Correlation between the SPI and variability shown by NAO and ENSO indices describes the control of

rainfall variability in Morocco by global climate variability, thus displaying teleconnections.

First, the connection between CWT classes and rainfall for the three regions is presented for winter months (Oct–Mar) and summer months (Apr–Sep) in figure I-5.2.4. During the winter, E and SE classes are negatively correlated with the SPI and are thus connected with dry conditions. Rainfall events belong mainly to the western classes and to the N class because air originating from these directions is maritime and moist. The anticyclonic class (AC) is only weakly connected with rainfall. The NE and S classes show no correlation. The correlation coefficients never exceed the level of 0.6, and thus one CWT class explains at maximum 36% of the rainfall variability. In general, the SOA SPI exhibits less correlation with CWTs. Correlations are generally much weaker during the summer. The SOA class shows an opposite behavior with positive correlations that are significant at the 95% level for the E class; the SE and S classes show larger but not significant

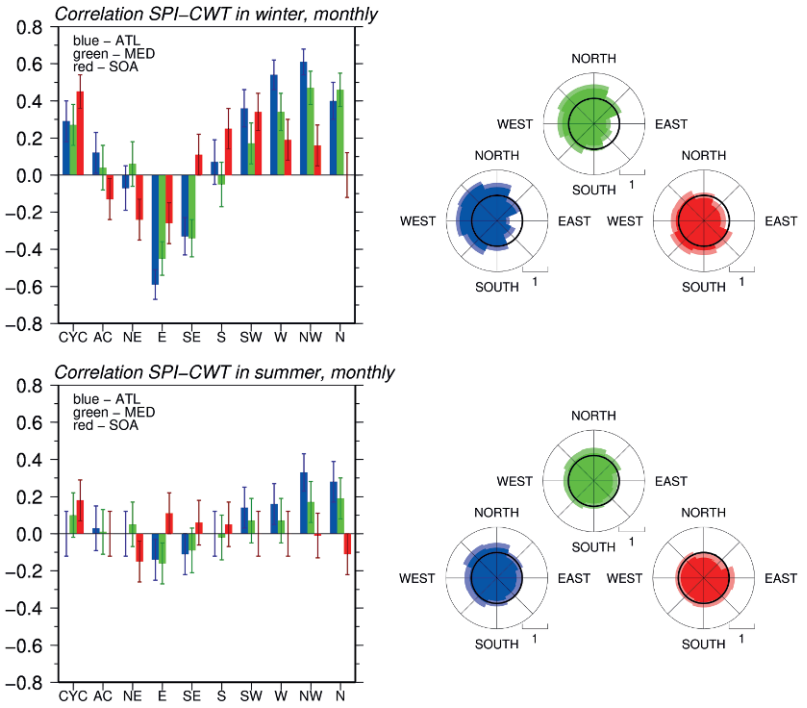

Fig. I-5.2.4: Left: Correlation between time series of relative frequencies of CWTs derived from NCEP data with the SPI series for the ATL, MED and SOA region for 1960–2006 obtained from GHCN data. Whiskers denote the 95% uncertainty limits. Right: For the directional classes, the results can be drawn in wind roses. Here correlation values inside the black circle of zero correlation denote dryer than mean conditions, outside the circle wetter than mean. The brightly shaded area denotes the 95% confidence interval. If the black circle lies outside this confidence interval, correlation is significant at the 95% level.

correlations. This is often due to the location of a trough over the Canary Islands (Knippertz 2003a, 2004; Knippertz and Martin 2005) and is sometimes connected with TEI. On the southeasterly flank of the trough, moist air is transported from the Atlantic in the southwest towards the southerly slope of the Atlas Mountains, and may lead to rainfall. The origin of the moist air can be traced by calculating backward trajectories. Origins are sometimes found in regions of the westerly tropical Atlantic or over tropical West Africa (Knippertz and Martin 2005).

The teleconnection of Moroccan rainfall with ENSO is shown in figure I-5.2.5a. The ATL and MED regions show increasing correlations with a time lag of 8–18 months, but the values are rather small, though statistically significant at the 95% level. It must be kept in mind that a correlation coefficient of 0.2 corresponds to only 4% of explained variance. In figure I-5.2.5b, the corresponding analysis is shown for the CWTs. Annual time series of the ENSO index and CWT classes generally show weak relationships, although the negative correlation of S and SE classes and the positive correlation of W and NW to ENSO appear to be systematic. ENSO has been shown to affect tropical convection in Western Africa and the Sahel region (Ward et al. 1999). This may cause a weak influence of ENSO on S and SE CWTs, since these classes are most likely affected by TEI events (Knippertz 2003a, subsect. I-5.2.3).

Because a high NAO index corresponds to strong zonal flow, more moist Atlantic air is transported towards central Europe. From this mechanism, we expect the Moroccan rainfall to be negatively correlated with the NAO index. In fact, lag-correlation series between the NAO index and the SPI values show high correlations for the ATL and MED regions (see fig. I-5.2.5b). The high correlation values for a period of up to 12 months after a high NAO index indicate that the NAO index tends to remain at a similar state for about a year. The SOA region is hardly affected by variability of the NAO. The relation between the annual NAO index and

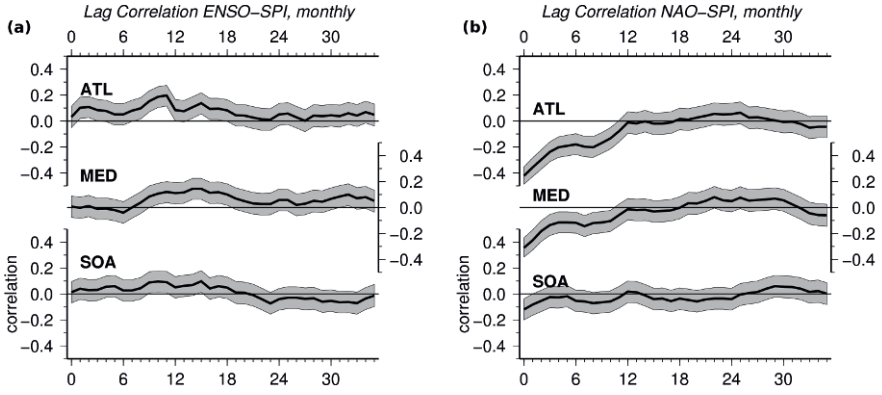

Fig. I-5.2.5: Lag correlation of the monthly ENSO (a) and NAO index (b). (Source: CRU; Jones et al. (1997), extended by Osborn (2006); SPI values from GHCN for 1960-2006). The grey shaded range marks the 95% confidence interval.

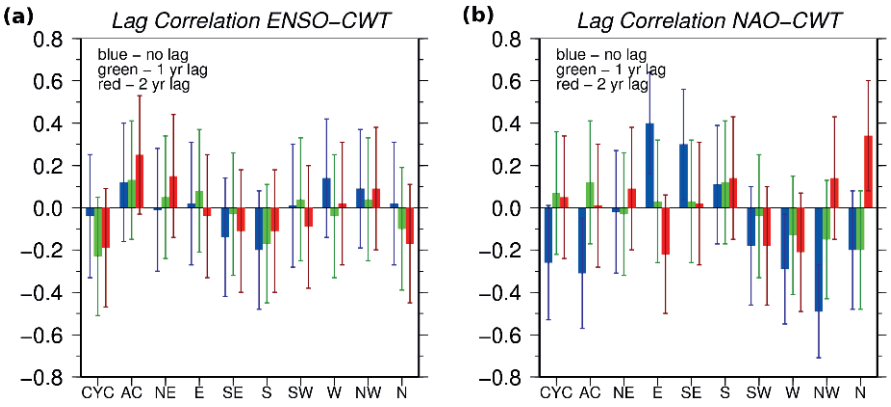

Fig. I-5.2.6: Lag correlations of the annual ENSO (a) and NAO (b) indices (average Sep-Aug) with CWT classes for the period 1960-2006. Whiskers show the 95% interval of uncertainty for the correlation coefficients.

the occurrence of CWT classes is shown in figure I-5.2.6b. Correlations for the easterly E/SE classes and the westerly W/NW classes are barely statistically significant at the 95% level. There is no remarkable lag-correlation for more than 12 months.

When using the ENSO and NAO variability as predictors for the SPI, a multiple regression reveals that the total explained variance never exceeds 20%. Exemplary results with 0- and 9-month lag times with respect to the ENSO signal are shown in table I-5.2.1. Using the ENSO index with lag – preceding the SPI – reveals that the ENSO-SPI relation is at a maximum after 9 months.

Table I-5.2.1: Results of the multiple regression using monthly NAO and ENSO indices as predictors for the SPI in the three Moroccan regions; the ENSO is taken 0 and 9 months in advance. The data were transformed into anomalies from the mean annual cycle. Bold numbers indicate correlations, which are responsible for more than 30% of the total explained variance.

Lag in months		ATL	MED	SOA
0	correlation ENSO-SPI	0.035	0.029	0.009
	correlation NAO-SPI	**-0.429**	**-0.327**	**-0.124**
	total explained variance	18.5%	10.8%	1.5%
9	correlation ENSO-SPI	**0.136**	**0.158**	0.052
	correlation NAO-SPI	**-0.428**	**-0.323**	**-0.127**
	total explained variance	20.0%	12.8%	1.9%

It is well known that precipitation is one of the most stochastic weather parameters. With respect to seasonal predictions using simple statistical relationships, the results suggest that large-scale variability caused by the NAO and ENSO controls Moroccan rainfall variability towards a detectable but relatively small range. From this point of view, one should not expect these indices to deliver sufficient results for an assessment of seasonal rainfall prediction. Other candidates for predictors, such as Atlantic SSTs, are connected to NAO or ENSO variability and do not show higher predictive skills. Therefore, in terms of predictability by teleconnection with ENSO/NAO features, a reasonable part of Moroccan rainfall variability remains stochastic and can only be assessed by applying more complex atmospheric climate or weather prediction models.

I-5.2.3 Summer precipitation and convective density currents

In contrast with areas north and west of the Atlas Mountains, whose climates are clearly dominated by winter precipitation (Knippertz 2003a), stations within the Drâa catchment receive significant contributions to their annual precipitation from rainfalls during summer months, particularly in May and from August to October (see fig. I-4.3.2). These rainfall events are often related to the formation of deep moist convection over the High Atlas Mountains (i.e., thunderstorms or showers) that form underneath or ahead of weak upper-level troughs (i.e. at levels between 5 and 12 km asl) when approaching the region from the Atlantic (Knippertz et al. 2003b). For several cases of significant late summer/early autumn precipitation, Knippertz et al. (2003b) traced the moisture back to sources over tropical West Africa, where the monsoon rainy season reached peaks during this time of the year. Based on backward trajectories started in rain zones over northwestern Africa, Knippertz et al. (2003b) show that poleward moisture transport is often caused by interactions between westward-moving troughs of moist African easterly waves in the lower troposphere of tropical western Africa and eastward-moving (or stationary) troughs in the upper-troposphere of the subtropics (see fig. I-5.2.7); Nicholson (1981) had already suggested this theory. A climatological analysis of backward trajectories revealed that this transport path occurs most frequently during August and September, when 65% of all precipitation recorded at Ouarzazate is connected to this particular flow configuration (Knippertz 2003b). Significant contributions are also found during au-

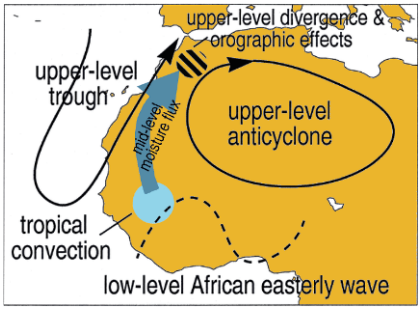

Fig. I-5.2.7: Schematic depiction of the transport of tropical moisture into Northwestern Africa (Source: Knippertz 2003b).

tumn (October and November), while the West African tropics during the spring are too dry to feed rainfall farther north. Up to 40% of the annual precipitation at Ouarzazate can be linked to an inflow of moist air from the West African tropics or the nearby tropical Atlantic towards northwest Africa. Investigations of single cases suggest that the convection is triggered by near-surface convergence over the elevated heat source of the Atlas Mountains during the afternoon, which is supported by dynamical lifting and low vertical stability associated with the upper trough.

During the warm season, the planetary boundary layer (PBL) over the Saharan part of Morocco is usually very deep and well-mixed during afternoon hours (Knippertz et al. 2009a). High near-surface temperatures and low relative humidity provide enormous potential for the evaporation of precipitation. In situations with westerly or northerly vertical wind shear, hydrometeors formed in deep moist convection over the crest of the Atlas Mountains are blown to the Saharan side of the mountains, where a large portion of associated precipitation evaporates. The neutral stratification in the PBL allows evaporatively-cooled air to accelerate downwards to the surface, where the cold pool spreads horizontally as a density current with a sharp leading edge (Knippertz et al. 2007; see fig. I-5.2.8). Typically, the passage of this leading edge across the Saharan forelands of the Atlas Mountains is accompanied by changes in wind direction, marked increases in dew point, wind speed and pressure, and decreases in temperature and visibility due to the presence of freshly mobilized dust (Knippertz et al. 2007; Emmel et al. 2009). The cold pools can reach horizontal extensions of several hundred kilometers and lifetimes of up to 10 hours. With typical propagation velocities on the order of 6 m s^{-1}, they can reach far into the Sahara of western Algeria.

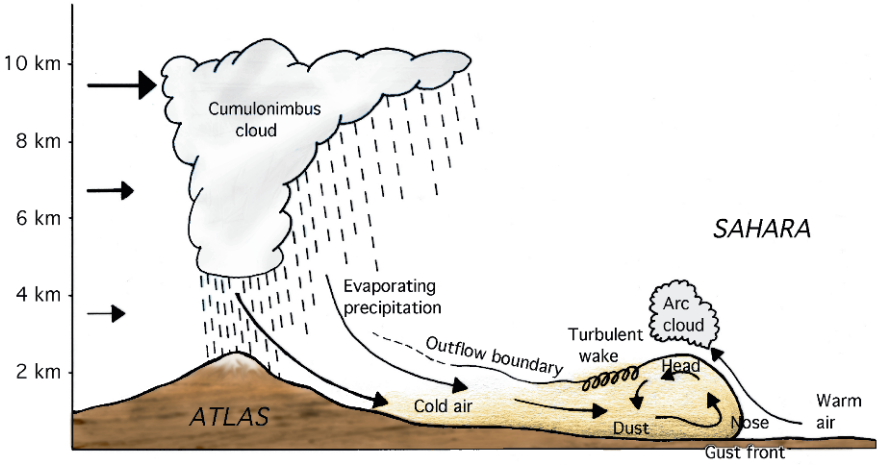

Fig. I-5.2.8: Schematic depiction of the formation of convective density currents at the southern side of the High Atlas Mountains in summer. For details see text (Source: Knippertz et al. 2007).

High-resolution numerical simulations by Knippertz et al. (2009b) demonstrate that the leading edge is associated with concentrated deep ascent under conditions of sufficient vertical wind shear. These conditions re-generate deep moist convection on the Saharan side of the Atlas Mountains, allowing the whole system to propagate from the High Atlas Mountains into the foothills. Shallow arc clouds may form only in situations of unfavorable shear or vertical stability (see fig. I-5.2.8). These results suggest that the squall-line mechanism of convective organization is important to bring rainfall into the northern Sahara during summer months, even though increasingly deep and dry sub-cloud layers cause ground precipitation rates to decrease away from the mountains. A climatological analysis of density currents over the southern Drâa catchment reveals a clear occurrence maximum in the warm season, primarily during August and September (Emmel et al. 2009). The prevalence during the second half of the day indicates a close connection to the diurnal cycle of deep moist convection. Composite studies reveal that density-current days are preceded by periods of moisture transport from tropical West Africa ahead of a weak upper-level trough (see Knippertz et al. 2003d and discussion above) that finally passes over the region to the east.

I-5.2.4 Conclusions

Meteorological research within IMPETUS has shed some new light on the processes pertinent to the rainfall variability south of the Atlas mountain divide. Here, tropical-extratropical interactions often trigger extreme rainfall events fed by tropical moisture sources. The frequency of occurrence of these events peak in fall and spring, but they also occur in winter and summer. During the later season, precipitation is often related to thunderstorms and showers triggered over the Atlas Mountains. Evaporation associated with this convection generates extended pools of cool air that transport moisture into the northwestern Sahara and mobilize soil dust. In contrast to winter precipitation, these phenomena have been studied very little.

It was also shown that Moroccan rainfall variability is significantly (in a statistical sense) connected to the large-scale climate phenomena ENSO and NAO. However, the variance explained is insufficient to be exploitable for statistical seasonal prediction of rainfall using ENSO and NAO indices as predictors. This finding and the studied complex mechanisms responsible for rainfall variations at various spatio-temporal scales corroborate the need to apply complex atmospheric modeling and regionalization approaches over the entire range of climatic scales to obtain meaningful climate projections. These approaches are described in section II-3.2.

References

Bordi I, Fraedrich K, Petitta M, Sutera A (2006) Extreme value analysis of wet and dry periods in Sicily. Theor Appl Climatol 87:61-71

Born K, Fink A, Paeth H (2008) Dry and wet periods in the northwestern Maghreb for present day and future climate conditions. Meteorol Z 17:533-551

Emmel C, Knippertz P, Schulz O (2009) Climatology of convective density currents in the southern foothills of the Atlas Mountains. J Geophys Res. doi:10.1029/2009JD012863

Jones PD, Jonsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int J Climatol 17:1433-1450

Jones PD, Hulme M, Briffa KR (1993) A comparison of Lamb weather types with an objective classification scheme. Int J Climatol 13:655-663

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa L, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C,Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-Year Reanalysis Project. Bull Am Meteor Soc 77:437-471

Knippertz P (2003a) Niederschlagsvariabilität in Nordwestafrika und der Zusammenhang mit der großskaligen atmosphärischen Zirkulation und der synoptischen Aktivität. In: Kerschgens MJ, Neubauer FM, Pätzold M, Speth P, Tezkan, B (eds) Mitteilungen aus dem Institut für Geophysik und Meteorologie der Universität Köln, Vol. 152, pp. 136. Cologne

Knippertz P (2003b) Tropical-extratropical interactions causing precipitation in Northwest Africa: Statistical analysis and seasonal variations. Mon Weather Rev 13:3069-3075

Knippertz P, Christoph M, Speth P (2003a) Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorol Atmos Phys 83:67-88

Knippertz P, Fink AH, Reiner A, Speth P (2003b) Three late summer/early autumn cases of tropical-extratropical interactions causing precipitation in Northwest Africa. Mon Weather Rev 131:116-135

Knippertz P (2004) A simple identification scheme for upper-level troughs and its application to winter precipitation variability in Northwest Africa. J Climate 17:1411-1418

Knippertz P, Martin JE (2005) Tropical plumes and extreme precipitation in subtropical and tropical West Africa. Q J Roy Meteor Soc 131:2337-2365

Knippertz P, Deutscher C, Kandler K, Müller T, Schulz O, Schütz L (2007) Dust mobilization due to density currents in the Atlas region: Observations from the SAMUM 2006 field campaign. J Geophys Res 112. doi:10.1029/2007JD008774

Knippertz P, Ansmann A., Althausen D, Müller D, Tesche M, Bierwirth E, Dinter, T, Müller T, von Hoyningen-Huene W, Schepanski K, Wendisch M, Heinold, B, Kandler K, Petzold A, Schütz L, Tegen I (2009a) Dust mobilization and transport in the northern Sahara during SAMUM 2006 – A meteorological overview. Tellus 61B:12-31

Knippertz P, Trentmann J, Seifert A (2009b) High-resolution simulations of convective cold pools over the northwestern Sahara. J Geophys Res 114. doi:10.1029/2008JD011271

Lamb PJ, Peppler RA (1987) North Atlantic Oscillation: concept and application. Bull Am Met Soc 68:1218-1225

Lamb PJ, El Hamly M, Portis DH (1997) North-Atlantic Oscillation. Géo Observateur 7:103-113

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. Preprints, 8th Conference on Applied Climatology, pp. 179-184. January 17-22, Anaheim, CA

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high resolution grids. Int J Climatol 25:693-712

Nicholson SE (1981) Rainfall and atmospheric circulation during drought periods and wetter years in West Africa. Mon Weather Rev 109:2191-2208

Osborn TJ (2006) Recent variations in the winter North Atlantic Oscillation. Weather 61:353-355

Pinto JG (2002) Influence of large-scale atmospheric circulation and aroclinic waves on the variability of Mediterranean rainfall. In: Kerschgens MJ, Neubauer FM, Pätzold M, Speth P, Tezkan, B (eds) Mitteilungen aus dem Institut für Geophysik und Meteorologie der Universität Köln, Vol. 151, pp. 134. Cologne

Trenberth KE, Caron JM, Stepaniak DP, Worley S (2002) Evolution of El Niño–Southern Oscillation and global atmospheric surface temperatures. J Geophys Res. doi:10.1029/2000JD000298

Troup AJ (1965) The Southern Oscillation. Q J Roy Meteor Soc 91:490-506

Vose RS, Schmoyer RL, Steurer PM, Peterson TC, Heim R, Karl TR, Eischeid JK (1992) The Global Historical Climatology Network: Long-term monthly temperature, precipitation, sea-level pressure, and station pressure data. -- NDP-041. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Ward MN, Lamb PJ, Portis DH, El Hamly M, Sebbari R (1999) Climate variability in northern Africa: understanding droughts in the Sahel and the Maghreb. In: Navarra A (ed) Beyond El Niño – decadal and interdecadal climate variability, pp. 119-140. Springer, Wien





6 Continental hydrosphere

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I-6 Continental hydrosphere

B. Diekkrüger

Water is the key to sustainable development. It is necessary for domestic use, for husbandry, industry, and irrigation, and it is necessary for sustaining ecosystem functions. Water availability is, on one hand, dependent on meteorological conditions, and on the other, on terrestrial processes. According to Falkenmark and Rockström (2004), the ratio of blue to green water is determined at the boundary between the pedosphere and the atmosphere. In this concept, blue water is the visible part of the water, which is available at the surface or as soil water or groundwater. In contrast, green water is the non-visible part, which returns as water vapor into the atmosphere. Green water may be productive (transpiration) or unproductive (evaporation). Integrated Water Resource Management (IWRM) mainly concentrates on blue water, although conserving green water is an important aspect.

Sustainable water resource management requires a thorough knowledge of water availability and demand at different spatial and temporal scales. In addition, it is necessary to understand processes to evaluate the impacts of human activities (e.g., construction of reservoirs) or environmental changes (e.g., Climate Change, land use change). Sampling often takes place at very small spatial and temporal scales, sometimes smaller than the process scale. While the process scale depends on the problem to be solved or the question to be answered, the information scale is the scale on which information is required (e.g., for decision-making). The model scale is situated between these different scales. Temporal and spatial discretization must take into account the sampling and the process scale as well as the information scale. Scale consideration and scaling is not only a question of hydrological analysis and hydrological modeling, but it is the key to successful Integrated Water Resource Management (Loucks et al. 2005). Treating the catchment as a whole may be sufficient for reservoir management, but usually decisions have to be made at the local scale. Therefore, IWRM requires knowledge within the catchment that considers the spatial and temporal variability of the water balance. The chosen approaches consider these requirements. Spatial and temporal distributed hydrological analyses and simulations are performed in order to identify cause-effect relationships, which are a prerequisite for scenario analysis as described in part II of this book.

Besides hydrology, soil is another important resource for sustainable development. Deterioration of soil quality has different reasons, one of them being soil erosion by water. In addition to gully erosion and badland development, which is directly visible to anyone, soil erosion is also often a creeping hazard that is difficult to recognize and quantify. Scale issues are also of importance if one deals with soil erosion by water. At the local scale, soil erosion is the dominant process leading to a decrease in soil thickness. At the hillslope scale, deposition at the slope foot may result in a local increase in soil thickness, and it is often related to

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an increase in soil fertility. Erosion, therefore, increases soil heterogeneity. At the catchment scale, channel and river processes gain increasing significance. While high erosion rates are observed at the local scale, sediment yield, which is the net transport out of the catchment, decreases with increasing size of the catchment. Nevertheless, while sediment yield is of importance for off-site damage, like the siltation of reservoirs, plot scale erosion threatens soil fertility and, therefore, crop yield. Water, erosion and sedimentation have to be studied together to be able to consider most of the feedback processes. In Benin and Morocco, soil is a scarce resource that is not renewed within the human timescale. Yet soil erosion does not only threaten soil fertility, it also significantly reduces the water-holding capacity of shallow soils. Fertility decline results from the loss of scarce humus content and fine material having a larger cation exchange capacity. Furthermore, off-site damage is of high importance as downstream ecosystems are threatened or reservoir capacity is lost.

In this chapter, results from the work of hydrologists and hydrogeologists are presented. The research concept differs between the countries under investigation. In Benin, a concept was developed that starts at the small catchment scale (a few km²) for studying hydrological processes, as data dependent on climate and land use in West Africa was limited. The key was to quantify the impact of land use on the ratio of blue to green water. The findings were transferred to scales up to 50,000 km². In contrast to this hierarchical approach, the hydrological analysis in Morocco follows a local scale approach following the gradient in temperature and rainfall on the one hand, and on the other a regional approach for quantifying run-off. In between both approaches is the linear oases structure, in which water consumption as well as soil salinity is studied. For studying soil erosion, such a hierarchical approach would also be of benefit. However, the scale problem is even larger in soil erosion science than in hydrology. Therefore, this study follows a regional approach that identifies erosion hot spots. These will need to be further analyzed with alternate methods.

References

Falkenmark M, Rockström J (2004) Balancing water for humans and nature – the new approach in ecohydrology. Earthscan Publications, London

Loucks DP, van Beek E, Stedinger JR, Dijkman JPM, Villars MT (2005) Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Study and reports in Hydrology. Unesco Publishing. http://ecommons.library.cornell.edu/handle/1813/2804 Accessed 02 September 2009

I-6.1 Hydrological processes and soil degradation in Benin

S. Giertz, C. Hiepe, G. Steup, L. Sintondji, and B. Diekkrüger

Abstract

Hydrological processes in sub-humid tropics like Benin are driven by climate (rainy season – dry season), land use, and the distribution of soil properties. To differentiate between these factors, field experiments have been carried out. Measurements of infiltration and hydraulic conductivity reveal the impact of land use on soil properties and, therefore, on runoff generation processes. Surface runoff, and with it erosion, is aggravated under agricultural use. Within the vadose zone, lateral flow processes are predominant. The physically based SIMULAT-H model was developed and applied successfully at the local scale. This model was used to both verify process understanding and to quantify the effects of land use and climate on discharge. It was also used as a benchmark for a conceptual model applied at the regional scale. The conceptual semi-distributed model UHP-HRU (Universal Hydrological Program – Hydrological Response Unit) is able to simulate regional scale water fluxes up to decades. It has been successfully calibrated and validated at a number of gauging stations at different spatial and temporal scales. The results show that discharge is more influenced by climate than by land use, which more affects runoff components (surface runoff vs. interflow and baseflow). As UHP-HRU is sensitive to land use, soil and climate, it was used for scenario analysis in a following step.

Severe rainfall events in combination with agricultural land use are the cause for soil erosion, which results in decreased soil fertility. The model system SWAT (Soil Water Assessment Tool) was used to simulate the erosional processes in the Upper Ouémé valley. The model was calibrated and validated successfully using discharge as well as turbidity data. The spatial patterns of soil erosion hotspots is correlated with the land use pattern, which itself is determined by population distribution.

Keywords: hydrological modeling, conceptual models, physically based models, runoff generation processes, spatial variability, model calibration, model validation, soil erosion, erosion modeling

I-6.1.1 Introduction

Analysis of the impact of Global Change on hydrological and erosional processes requires a thorough understanding of the processes as well as calibrated and validated simulation models. To achieve these goals, a "super test site" measurement concept was adopted in hydrology, i.e. small catchments were intensively gauged (see sect. I-4.1). From these local scale field investigations in the Aguima and Ara catchments, it became evident that lateral processes, such as surface runoff and interflow, are the most important. Therefore, after carefully analyzing the underlying processes and properties, the 1D-soil-vegetation-atmosphere-transfer (SVAT) model SIMULAT was modified to a hillslope version (SIMULAT-H). Concerning the runoff generation processes, a good agreement of simulation results and field investigations was achieved (see subsect. I-6.1.2). A physically based approach was not applicable to the regional scale due to limited information concerning soils and vegetation. Therefore, the discharge simulation was performed using the conceptual UHP-HRU model, which has been satisfactorily applied to a number of scales (see subsect. I-6.1.3). Due to the limited data requirements of UHP-HRU, it can be judged as suitable for application to catchments with limited input data availability, especially for long-term simulations that focus on the quantification of the water balance. Because the model is sensitive to climate and land use changes it was also applied to quantifying future scenarios (see sect. II-4.2).

Soil erosion simulation requires both a good representation of the hydrology, especially the surface runoff, and of the erosional and depositional processes. The model system SWAT was chosen in this study as it has been proven to be applicable at the regional scale. It considers the most important processes and their feedbacks and is sensitive to climate and land use changes. The validation of the model at different scales using discharge and turbidity data is promising (see subsect. I-6.1.4). The calibrated and validated model was used to calculate future hot spots of soil erosion in the Upper Ouémé valley (see sect. II-4.2)

I-6.1.2 Hydrological processes at the local scale

In order to develop and to apply hydrological simulation models, it is essential that the hydrological function of a catchment is understood. For this reason, hydrological processes were analyzed thoroughly on a local scale. To take into account the impacts of land use and land cover changes, three different catchments were analyzed: the upper Aguima catchment (3.2 km²), characterized by natural vegetation; the upper Niaou catchment (3.1 km²), a small tributary of the Aguima but dominated by agricultural land use; and the Ara catchment (13 km²), a tributary of the Donga river, which has been used agriculturally for a long time. Figure I-4.1.1 shows the location of the study sites. The catchments are located in the

sub-humid Sudan-Guinea-zone with a unimodal rainy season lasting from May to October (see sect. I-3.4). They are characterized by a flat, undulating pediplain relief with inland valleys in the headwater catchments. The underlying rock is granite or gneiss in different metamorphic grades, which is deeply weathered to clayey saprolite with a thickness of 15 to 25 m. According to the World Reference Base classification (FAO-ISRIC-ISSS 1998), the prevailing soil types are Acrisols, Lixisols and Plinthosols. Acrisols and Lixisols occur mainly on the middle part of the hillslope and are characterized by loamy sand in an ochric horizon and by clay accumulation in an argic horizon. Plinthosols are defined by a layer of an iron-rich mixture of clay minerals and silica that hardens on exposure into an impermeable ironstone crust. Plinthosols are often degraded shallow soils with high gravel content in the topsoil due to topsoil loss caused by soil erosion. They can be found at the bottom of the hillslope and near the drainage divide. Gleysols and Fluvisols are sandy soils of colluvial and alluvial material in inland valleys and at the borders of rivers.

Runoff generation processes

Total discharge is composed of overland flow and subsurface flow. Overland flow can be created by infiltration excess (Hortonian overland flow), saturation excess and return flow. Infiltration excess overland flow occurs when the rate of rainfall exceeds the infiltration rate of the soils. This process depends strongly on rainfall intensities and infiltration capacities. Figure I-6.1.1 shows the results of in-situ infiltration measurements on different soil types and land uses in the Ara catchment. On average, the infiltration rate on fields is one third of the rate under natural vegetation or when fallow. Comparable results were published by Giertz (2004) for infiltration experiments in the Aguima catchment. As most of the soils have loamy-sandy topsoils, the main differences are due to different land uses and not to different soil types. The reduced infiltration rates on cultivated plots are mainly caused by reduced activity of the soil fauna and, consequently, a reduction of biological macropores in the soil, which have a major impact on the saturated conductivity (Giertz et al. 2005). The measurements show a high spatial variability of infiltration rates, especially under natural vegetation and when fallow. When fields lie fallow after cultivation, the conductivity can reach values comparable to these under natural vegetation within two years, given that the soil is not yet completely degraded during cultivation. In severely degraded areas, where the topsoil is completely lost due to soil erosion, the infiltration rate remains low even after ten to twenty years of being fallow. Infiltration excess overland flow occurs mainly on cultivated and degraded areas.

Saturation excess overland flow can be observed on saturated flat areas at the foot slope, in inland valleys, and on degraded shallow soils. Inland valleys (in French: *bas-fonds*), which are regularly flooded during the rainy season, are widespread and therefore do have a high impact on the hydrology. The occurrence of

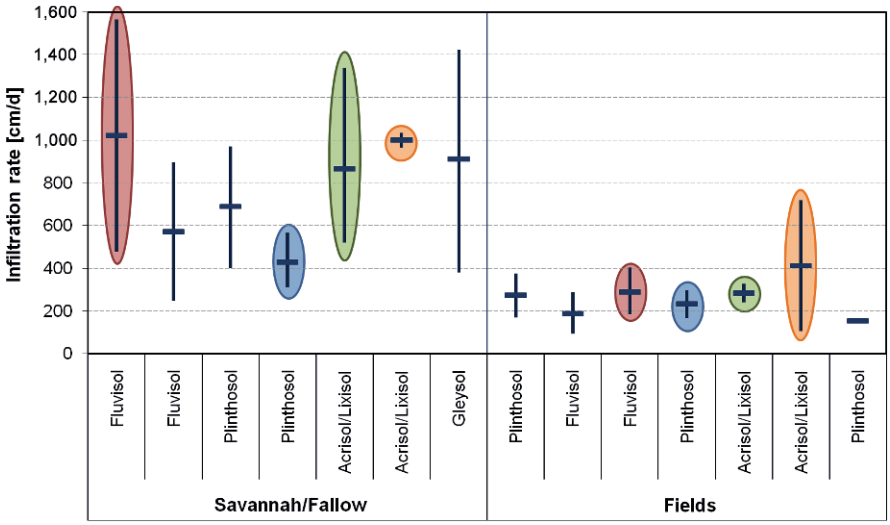

Fig. I-6.1.1: Infiltration rates measured on different soil types and different land covers. Crossbar: Arithmetic mean; tails: Minimum and maximum; circles: Same plot. Soil samples were taken in the Ara catchment, Benin (13 km², see fig. I-4.1.1). The data marked with the same color are measured on the same plot within a range of only a few meters, on the same soil type, but with different land cover.

saturation excess overland flow is dependent on the initial soil moisture at the beginning of a rainfall event, the rainfall amount and the storage capacity of the soils. Subsoils with low permeabilities promote saturation of the overlaying horizons, resulting in overland flow and interflow. Generally, the permeability decreases with depth. Measurements of soil cores from the Ara catchment have revealed that the saturated hydraulic conductivity of the topsoil is – under natural vegetation or fallow – on average less than 20% of the infiltration rate. In the B-horizon the mean conductivity ranges between 2 cm per day in clayey soils and more than 300 cm per day in sandy Gleysols. Especially shallow Plinthosols with an impermeable plinthic horizon do not have a large storage capacity, and they contribute to saturation excess overland flow. Whether inland valleys promote saturation excess overland flow is strongly dependent on their water-filling level. As long as they are not saturated at the beginning of the rainy season, the storage capacity of inland valleys is filled by rainfall and lateral flows caused by surface runoff and interflow. A baseflow contribution from the saprolitic aquifer is also possible. In this period, inland valleys act as a buffer and have smooth peak flows during and after rainfall events. When the storage capacity is reached, the hydrological behavior changes completely. The inland valleys now form large saturated areas that intensify saturation excess overland flow and peak flows.

Return flow is linked to the occurrence of interflow generated in the unsaturated zone, when there is a clear decline of saturated conductivity that leads to

local saturation and lateral flow. This process primarily takes place in Plinthosols with an impermeable plintic horizon and in Gleysols, where sandy colluvial and alluvial horizons with high permeabilities lay over impermeable clayey layers. Measurements of saturated hydraulic conductivities on soil cores from the Ara catchment showed that there is no considerable difference between lateral and vertical conductivity (see fig. I-6.1.2). But preferential flow paths were not taken into account in these measurements. Macropores created by earthworms, termites and ants can contribute to fast percolation or interflow. In Gleysols with sandy horizons over impermeable clayey layers, pipe erosion caused by interflow can be observed. At the lower slope, interflow can exfiltrate from shallow Plinthosols and form the so-called return flow.

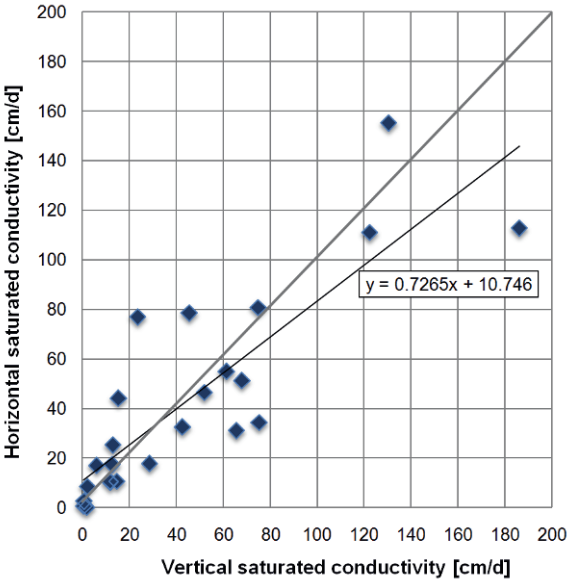

Fig. I-6.1.2: Scatter plot of vertical and lateral saturated hydraulic conductivities. Soil samples taken from the Ara catchment, Benin (13 km², see fig. I-4.1.1).

The generated overland flow can infiltrate before reaching the riverbed, especially in the sandy soils of the hydromorphic zone surrounding the valley bottom. However, overland flow often accumulates on preferential flow paths, such as on small footways through the savannah, that act as a drainage network during rainfall events. This results in a rapid contribution of one fraction of the overland flow to the discharge during and after rainfall events.

In Acrisols and Lixisols, percolation is the dominant process. Water that percolates to the saturated zone contributes to groundwater flow. In this region, two different aquifers can be distinguished. One of them is a shallow aquifer in the saprolite that is in hydraulic connection with a deep aquifer in the fractured bedrock. Hydrochemical analysis has revealed that in small catchments, the deep aquifer hardly contributes to the river discharge (Faß 2004; Kamagate et al. 2007). To what extent water from the saprolite aquifer reaches the stream flow is controversial. Faß (2004) determined by hydrochemical analysis that 25% of the stream flow in the Aguima catchment consists of water from the saprolite aquifer, whereas Kamagate et al. (2007) assumed little or even no input from this aquifer in the Donga catchment, which is the superior catchment of the Ara river. However,

water in the saprolite aquifer is not homogenous, spatially or temporally. The mean residence time can vary significantly with depth, resulting in difficulties in obtaining representative saprolite water samples. Furthermore, observations of preferential flow paths alongside the bands of the weathered parent rock show that there is likely a fraction of saprolite water that contributes to stream flow. In the Ara catchment, seasonal, perched water tables in the soil, recognized in the rainy season (Kamagate et al. 2007), can promote both continuous interflow and percolation.

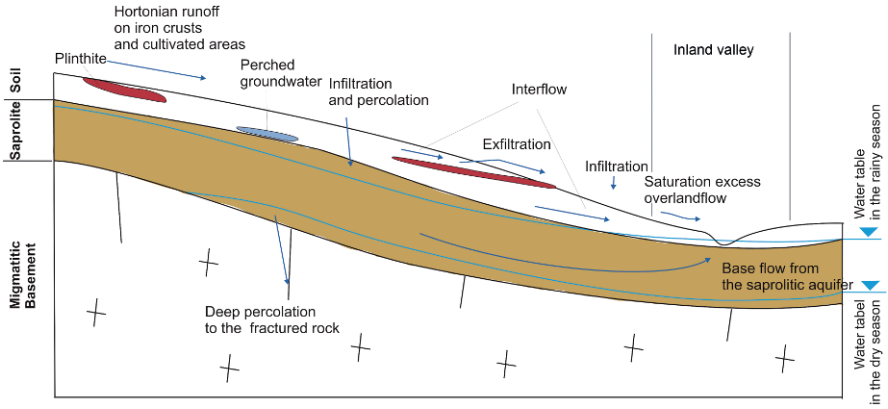

Fig. I-6.1.3: Conceptual model of the runoff generating processes in the investigated catchments.

Figure I-6.1.3 shows the conceptual model of runoff generation processes in the investigated catchments. These processes are mainly determined by soil properties and land cover. Hortonian overland flow and the fraction of surface runoff that reaches the river through preferential flow paths are dependent on the actual land use. Saturation excess overland flow is to a lesser extent dependent on actual land use than on soil physical properties. Of course, soil physical properties can be, over the long-term, the result of land use. Inland valleys represent large surface reservoirs that play an important hydrological role by retaining lateral inflows at the beginning of the rainy season and by contributing to saturation excess overland flow when they are saturated.

Physically based hydrological modeling

To simulate the hydrological processes at the local scale, the physically based model SIMULAT-H was applied. This model is based on the 1-D-SVAT-model SIMULAT (Diekkrüger and Arning 1995). Figure I-6.1.4 shows the model concept. Potential evapotranspiration was calculated with the Penman-Monteith equation.

The actual evaporation was calculated with the empirical approach of Ritchie (1972) and the actual transpiration with the approach of Feddes et al. (1978). The soil water fluxes were calculated using Richard's equation. In this equation, the interflow was considered as a sink and was calculated as a product of the lateral conductivity and the slope. Infiltration and surface runoff was calculated with a semi-analytical solution of Richard's equation based on Smith and Parlange (1978). A detailed model description can be found in Giertz et al. (2006a) and in Giertz (2004). In order to take the lateral flow processes into account, the hillslope version, SIMULAT-H, was developed. The concept of this modified SIMULAT version is shown in figure I-6.1.4. The catchment was discretized into hillslopes using the TOPAZ tool (Topographic Parameterization Tool of Garbrecht and Martz 1997). The hillslopes were divided into homogeneous soil units based on a detailed soil map. A conceptual linear groundwater model was integrated to simulate base flow from the saprolitic aquifer.

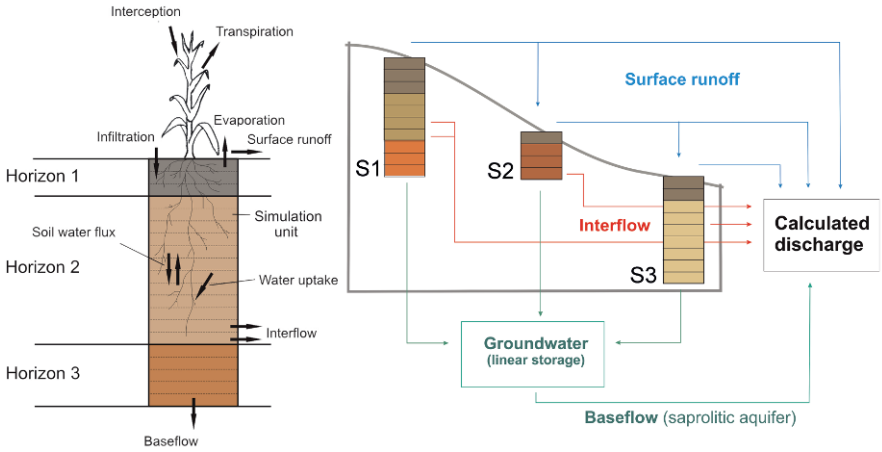

Fig. I-6.1.4: Model concept of the SVAT SIMULAT (left) and the spatially distributed version SIMULAT-H (S=Soil).

Giertz et al. (2006a) carried out a multi-criteria validation of the model in different sub-catchments of the Aguima. After calibrating the model for the Upper Aguima catchment (3.2 km²) for the year 2002 (model efficiency (ME) = 0.82, coefficient of determination (R^2) = 0.82), a successful validation was carried out for other sub-catchments of the Aguima and other time periods (2001-2003). In addition to the discharge, the discharge components, and the soil moisture were validated.

Figure I-6.1.5 shows the measured and simulated discharge for the years 2001 to 2003 and for 2006 on a daily time step for the upper Niaou catchment (3.1 km²). The years 2004 and 2005 could not be simulated due to missing precipitation and discharge data caused by failures of the measuring systems. The model was

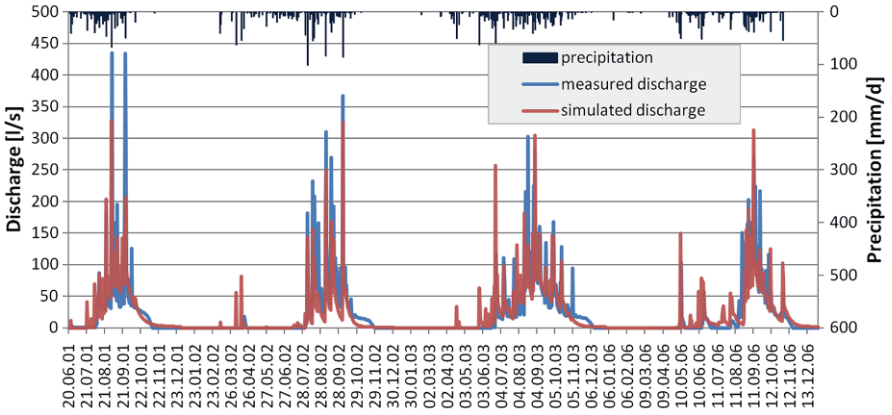

Fig. I-6.1.5: Measured and simulated hydrograph of the Upper Niaou catchment (3.1 km²) on a daily basis.

calibrated for the year 2002. All soil physical properties were taken from measurements and were not used for calibration. To integrate preferential flow paths of surface runoff, one portion of the simulated overland flow was immediately added to the river discharge without reaching the subsequent soil unit. As there were no reasonable data available, two important components had to be adjusted by calibration: the proportion of generated surface runoff that contributes directly to the discharge and the percentage of water from the saprolite aquifer that reaches the river. The most reasonable model performance was reached with a value of 30% for both parameters. These values are not easily transferable to other catchments. In larger catchments, where the riverbed lies on the granitic bedrock, it is probable that the contribution from the saprolitic aquifer increases. The percentage of the surface runoff directly reaching the river system is dependent on rainfall intensities, but this process is not yet integrated into the model system.

Table I-6.1.1 shows the model criteria measures for the simulations. The model results confirm the conceptual model (see fig. I-6.1.3) and the analysis of the hydrological processes. Surface runoff is primarily generated in areas under cultivation, on degraded shallow Plinthosols and on saturated areas. Acrisols and Lixisols under natural vegetation are dominated by vertical flow processes such as infiltration and percolation. Inland valleys strongly influence the hydrological behavior of the catchments. At

Table I-6.1.1: Model performance measures (calibration period 2002).

	Model Efficiency	R^2	Index of Agreement
2001	0.61	0.61	0.86
2002	0.77	0.82	0.92
2003	0.66	0.67	0.90
2004	0.52	0.76	0.89

the beginning of the rainy season, the discharge is often overestimated by the model. This can be explained by the infiltration of water in the dry riverbed not yet included in the model. One of the main uncertainties in the modeling process is the quality of the precipitation data as the initial input parameter for rainfall-runoff modeling. As the spatial variability of precipitation is very high in this region, several discharge peaks can be observed without any measured precipitation. Taking this uncertainty into account, the quality of the simulations is satisfying, especially the process representation. A further discussion of the uncertainties of the model application is published in Giertz et al. (2006).

I-6.1.3 Hydrological processes at the regional scale

Large scale pattern of land use and hydrological processes

On the regional scale, hydrological studies were carried out mainly in the largely investigated Upper Ouémé catchment (14,318 km^2), which is subject to rapid land use changes (see sect. I-7.1; Judex 2008).

The impact of land use on the hydrological processes at the plot and local catchment scale have been discussed in Giertz et al. (2006b), Giertz (2004) and in subsection I-6.1.2. These impacts were also detectable on the regional scale. This can be shown by analyzing the discharge data of sub-catchments with different land use and by using spatially distributed hydrological models. The discharge

Table I-6.1.2: Land use (year 2000) and hydrologic characteristics (mean values over the period 1993-2004) of different sub-catchments of the Upper Ouémé catchment.

	Aguimo	Térou-Saramanga	Térou-Igbomakoro	Ouémé-Beterou	Donga-Affon	Donga-Pont
land use [%]						
forest	34.4	10.0	18.1	6.8	1.6	1.4
savannah	59.3	75.0	69.6	75.2	68.4	66.9
cropland	1.5	13.8	10.9	15.5	28.6	30.4
settlements	0.0	0.2	0.1	0.1	0.3	0.4
other	4.9	1.0	1.3	2.4	1.1	0.9
hydrology						
total runoff [mm/y]	162	247	212	165	282	282
precipitation [mm/y]	1,249	1,325	1,324	1,189	1,277	1,303
runoff coefficient	0.13	0.19	0.16	0.14	0.22	0.22

data are available from the national hydrological service DGEau (*Direction Générale de l'Eau*) and IRD (*Institut de Recherche pour le Développement*) for 20 river gauges in the Ouémé catchment, whereof 9 are located in the Upper Ouémé catchment (see sect. I-4.1; Giertz 2008). The sub-catchments lying northwest of the Upper Ouémé catchment (Donga-Pont, Donga-Affon) show the highest proportion of cropland, while the catchments in the southwestern parts (e.g., Térou-Igbomakoro, Aguimo) have large areas of forest and savannah vegetation.

Table I-6.1.2 gives an overview of the land cover (year 2000) of different sub-catchments classified by Judex (2008) from Landsat7 images and the hydrologic characteristics of the catchments (mean values over the period 1993-2004). Only sub-catchments with continuous discharge data and without large data gaps were selected to assure the comparability of the data.

The runoff coefficient of the different sub-catchments clearly shows the impact of land use on the discharge volume. The higher the proportion of cropland and settlement, the higher is the runoff coefficient. Figure I-6.1.6 plots the runoff coefficient against the ratio of the cropland and settlement land use types. The R^2 value of 0.79 underlines the strong correlation between land use and runoff volume. A more detailed analysis of the spatial pattern of land use and hydrological process was carried out using a spatially distributed hydrological model.

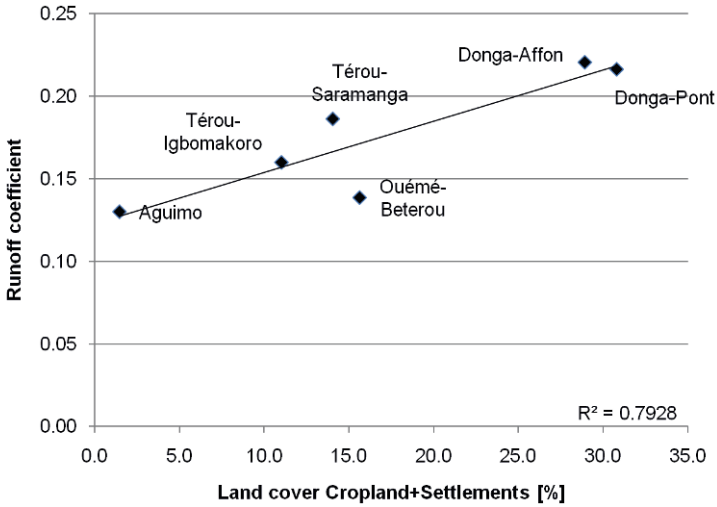

Fig. I-6.1.6: Correlation between land cover and runoff coefficients for different sub-catchments of the Upper Ouémé River. Size of the catchments: Aguimo 396 km², Terou-Igbomakoro 2,323 km², Terou-Saramanga 1,360 km², Ouémé-Beterou 10,083 km², Donga-Affon 1,308 km², Donga-Pont 587 km² (Data source: DGEau and IRD).

Regional hydrological modeling

In order to analyze the spatial pattern of the hydrological processes and the impact of land use and Climate Change on the water cycle, an adequate model is needed. It must be able to cope with low data availability, such as the physical soil properties on the regional scale in Benin. As the data requirements of a physically based model like SIMULAT-H cannot be fulfilled on the regional scale, a conceptual model was developed for regional scale modeling that incorporates the knowledge gained on the local scale, such as the importance of interflow.

In the first step, the lumped conceptual model UHP was developed (Bormann 2005). The model is able to simulate the discharge dynamics of different subcatchments of the Upper Ouémé catchment with a reasonable quality. The model was also tested successfully on the local scale (Giertz and Diekkrüger 2006c) in the Aguima catchment. In the second step, the semi-distributed UHP-HRU model was developed (Giertz et al. 2006b) in order to take into account the spatial heterogeneity of the catchment regarding soil and land use. UHP-HRU simulates all relevant hydrological processes such as evapotranspiration, surface runoff, interflow, percolation, and groundwater recharge. The model is composed of three linear storages: the root zone storage, the unsaturated zone storage and the saturated zone storage. They are linked via percolation and capillary rise. The potential evapotranspiration is optionally calculated with Penman (1956), Turc (1963) or Priestley and Taylor (1972). In this study the Penman equation was used. For the computation of the surface runoff, the SCS curve number approach was implemented in the model (SCS 1972).

The spatial discretization was carried out according to the hydrological response units (HRUs) concept. To define these HRUs, the catchment was subdivided into small sub-catchments with ArcHydroTools using the digital elevation model (DEM)

Table I-6.1.3: Input data for the hydrological modeling, Upper Ouémé catchment (14,318 km²).

	Number/spatial resolution	Source
climate data	2 stations	DMN, IMPETUS
precipitation	18 gauges	IRD, IMPETUS
soil map	1:200,000	ORSTOM 1977
soil parameters	40 representative profiles	Hiepe 2009, Sintonij 2005, ORSTOM 1976
land use	2 maps (1991 and 2000) 28.5*28.5 m	Judex 2008, classified from Landsat images
DEM	90*90 m	SRTM

Table I-6.1.4: Input data for the hydrological modeling, whole Ouémé catchment (gauge Bonou, 49,285 km²).

	Number/ spatial resolution	Source
climate data	5 stations	DMN, IMPETUS
precipitation	37 gauges	IRD, IMPETUS
soil map	Benin: 1: 200,000 Nigeria: 1:1,300,000	Benin: ORSTOM 1976 Nigeria: Sonneveld 1997
soil parameters	40 representative profiles	Hiepe 2008, Sintonji 2005, ORSTOM
land use	933 m*933 m	classified MODIS image
DEM	90*90 m	SRTM

from the SRTM mission (Shuttle Radar Topography Mission). A further subdivision in HRUs was performed by superposition with a soil and a land use map.
Compared to the version discussed in Giertz et al. (2006b), the version of UHP-HRU (Version 2.5) presented here comprises a routing routine for the river discharge and implies the possibility of implementing reservoirs, which is an important option to assess the impact of reservoir construction, such as for irrigation or hydropower.

In this study, spatially variable rainfall data were used instead of a mean value for the whole Upper Ouémé catchment, as used in Giertz et al. (2006b). This ensured a better representation of the hydrological processes, especially of surface runoff. In total, 18 rain gauges were used for the Upper Ouémé (14,318 km^2) and 37 gauges were used for the whole Ouémé catchment (gauge Bonou, 49,285 km^2, Giertz 2008). Only rain gauges were selected, which provided a continuous time series for the whole simulation period. The rain gauges were allocated to the sub-catchments with the Thiessen-Polygon method. An overview of the input data used in this study is given in tables I-6.1.3 and I-6.1.4.

Calibration and Validation

The new model version of UHP-HRU was calibrated for the Térou-Igbomakoro catchment (2,323 km^2) for the period 2003-2004 and was further validated for other sub-catchments and periods. The model calibration was carried out manually by modifying storage coefficients for interflow and groundwater, root depth, and curve number parameters.

Table I-6.1.5 gives an overview of the quality measures for the model calibration and validation for different sub-catchments of the Upper Ouémé for available discharge data of the period 1993-2004. For most of the catchments, the results

Table I-6.1.5: Measures of model performance for weekly discharges of different sub-catchments of the Upper Ouémé catchment (C= calibration, V= validation).

	Catchment Simulation						
	River	**Station**	**Size**	**Period**	**R^2**	**ME**	**Q_{sim}/Q_{mear}**
C	Terou	Igbomakoro	2,323	2003-2004	0.92	0.91	0.93
V	Terou	Igbomakoro	2,323	1997-2002	0.82	0.83	1.02
V	Terou	Wanou	3,060	1993-2000	0.72	0.67	1.11
V	Terou	Saramanga	1,360	1998-2004	0.75	0.77	0.87
V	Aguimo	Aguimo	396	1997-2004	0.65	0.63	0.96
V	Oueme	Bétérou	10,083	1993-2004	0.81	0.64	1.36
V	Donga	Affon	1,308	1997-2004	0.84	0.47	1.62
V	Donga	Pont	587	1998-2004	0.77	0.75	1.11

Table I-6.1.6: Measures of model performance for weekly discharge for different sub-catchments of the Ouémé catchment.

	Catchment Simulation						
	River	**Station**	**Size**	**Period**	**R^2**	**ME**	**Q_{sim}/Q_{meas}**
V	Ouémé	Bonou	49,285	1980-2002	0.83	0.78	1.22
V	Ouémé	Zangnanado	38,167	1986-1994	0.83	0.58	1.46
V	Ouémé	Save	23,491	1980-2002	0.80	0.77	1.33
V	Okpara	Kaboua	9,464	1980-1997	0.69	0.54	1.30
V	Zou	Atcherigbe	7,035	1980-1999	0.83	0.83	1.13

were good or satisfactory. Only for the Donga-Affon catchment (1,308 km^2) was the model efficiency relatively low. This was mainly caused by a high overestimation of some single events. The quality measures are comparable with the studies of Hiepe (2008) for the same catchments (see below), but better results were obtained for the Ouémé-Bétérou catchment (10,083 km^2), which covers most parts of the Upper Ouémé catchment. Figure I-6.1.7 shows that the hydrograph of the Ouémé at the Bétérou gauge is well reproduced by the model, taking into account the uncertainty of the input and validation data.

The amount of discharge is often overestimated at the beginning of the discharge period. This overestimation has also been reported by Giertz and Diekkrüger (2006c) and is visible in the simulation results of Varado et al. (2006). The surface runoff produced during high rainfall events at the beginning of the rainy season is often infiltrated at the valley bottom or in the dry riverbed. In most hydrological models, this effect is not implemented, which causes overestimation at the beginning of the discharge period.

After the successful calibration and validation for the Upper Ouémé catchment, the model was applied to the whole Ouémé (discharge gauge Bonou,

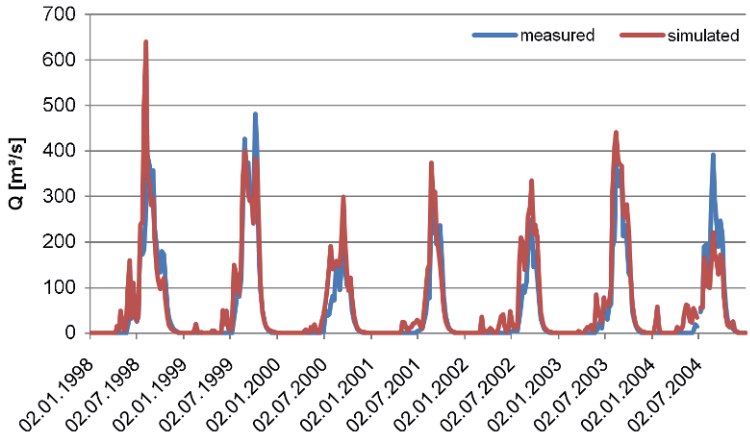

Fig. I-6.1.7: Simulated and measured weekly discharge of the Ouémé River, gauge Beterou (10,083 km²). (Data source: Discharge measurements from DGEau and IRD).

49,285 km²) without changing the model parameters. As the discharge data for validation and rainfall data were mostly available for longer periods than in the Upper Ouémé, a simulation period from 1980 to 2004 was selected. Table I-6.1.6 shows the quality measures for different sub-catchments of the Ouémé comprising the tributaries Zou and Okpara. Only stations with reliable data and relatively continuous time series were used for validation. Often, however, discharge data were not available before 2004. The model performance was good or satisfactory for all sub-catchments regarding model efficiency and R^2. However, an overestimation of discharge was observed for all sub-catchments. This can be explained by the land use map used in this study. For the whole Ouémé catchment, only MODIS-data with a low resolution (933 m x 933 m) were available for the year

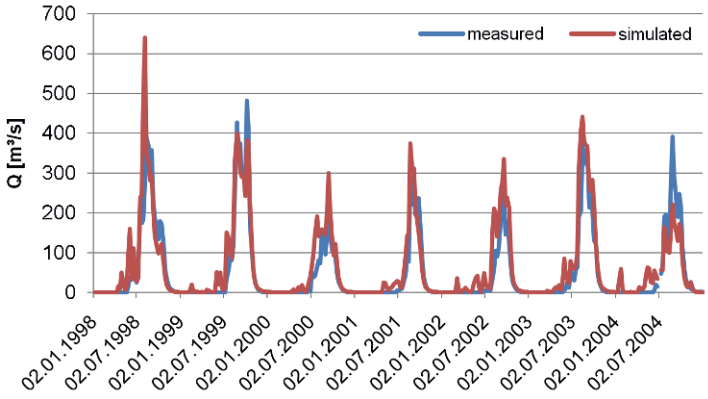

Fig. I-6.1.8: Simulated and measured weekly discharge of the Ouémé River, gauge Bonou (49,285 km²) (Data source: Discharge measurements from DGEau and IRD).

2002. This map was used for the whole simulation period. Analyses of Judex (2008) have shown that the fraction of cropland was much lower 1991 than 2000 in the Upper Ouémé, which is also true for the whole Ouémé catchment. Consequently, higher discharge volumes were simulated. The overestimation of discharge was also reported by Götzinger (2007), who carried out a simulation with the HBV-model for the same catchment within the framework of the RIVERTWIN-project.

Figure I-6.1.8 shows the simulated and observed discharge at the outlet of the catchment (Ouémé-Bonou). The discharge dynamic is well reproduced by the model in dry and wet years. However, in some years, over- and underestimation does occur. The recession and the drying of the river during the dry period are also well simulated by the model. This is not the case for the simulation results of Götzinger (2007) for the same catchment. In his simulation, the recession does not match the measured data, and in low flow periods, the simulated discharge is much higher than the measured discharge.

Considering the uncertainties in both the input data (land use, soils, precipitation data) and validation data, the model results of UHP-HRU can be evaluated as good for the Ouémé catchment.

Simulated water balance and spatial pattern

The simulated water balance for the simulation period 1993-2004 for the Upper Ouémé and selected sub-catchments is shown in table I-6.1.7. Due to the differences in land use, the actual evapotranspiration is lower and the total discharge is higher in the Donga-Pont catchment compared to the Térou-Igbomakoro catch-

Table I-6.1.7: Water balance (mean values over the period 1993–2004) for the Upper Ouémé catchment and selected sub-catchments.

	Upper Ouémé	Donga-Pont	Térou Igbomakoro	Upper Ouémé	Donga-Pont	Térou Igbomakoro
	mm/y	mm/y	mm/y	% of the rainfall		
Rainfall	1,213	1,303	1,324	100	100	100
Etpot	1,602	1,575	1,604	132	121	121
Etact	815	792	843	67	61	64
Qtotal	205	294	245	17	22	19
GW recharge	183	206	225	15	16	17
				% of the total discharge		
Qsurface	59	88	54	29	30	22
Qinterflow	125	175	148	61	59	60
Qbase	20	31	44	10	11	18

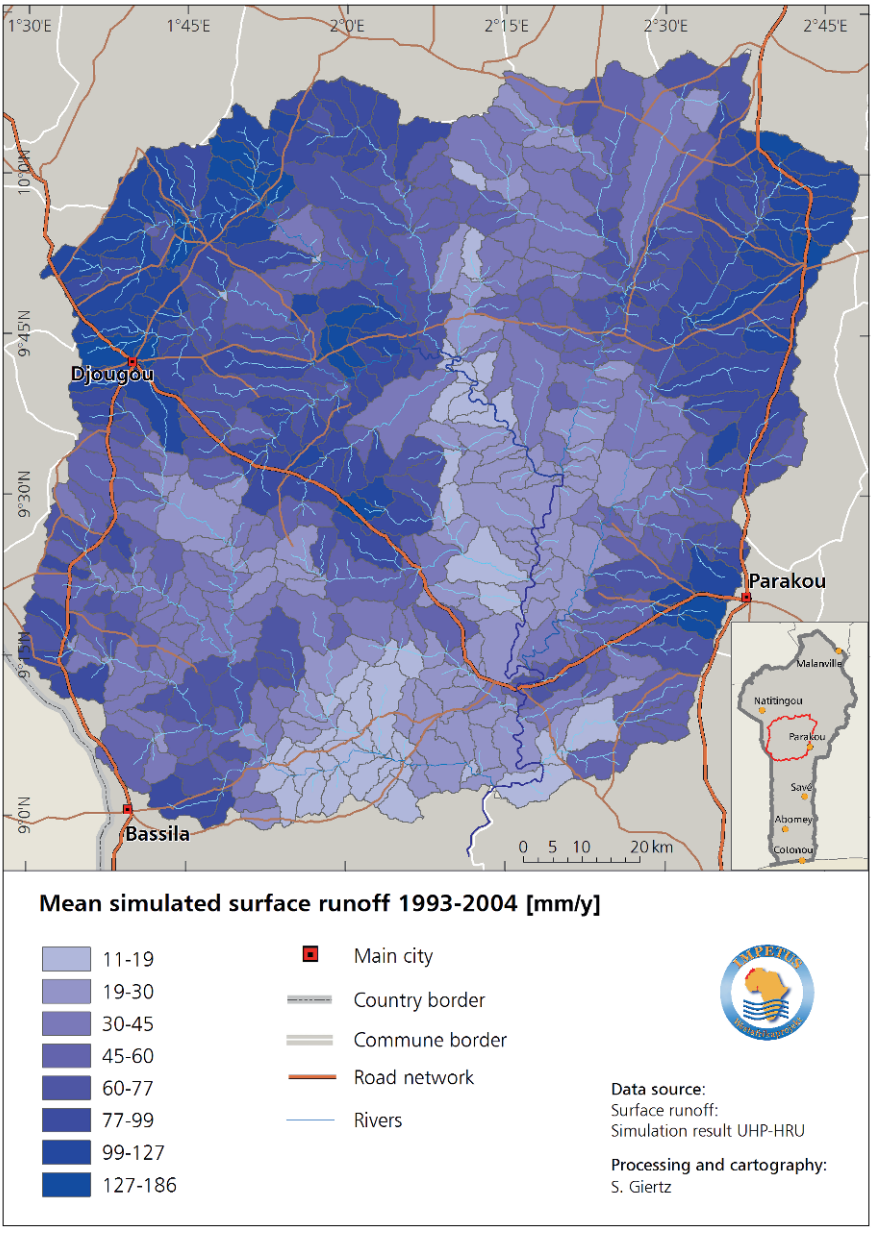

Fig. I-6.1.9: Spatial pattern of surface runoff in the Upper Ouémé catchment (14,318 km²) for the period 1993-2004 (simulation result UHP-HRU).

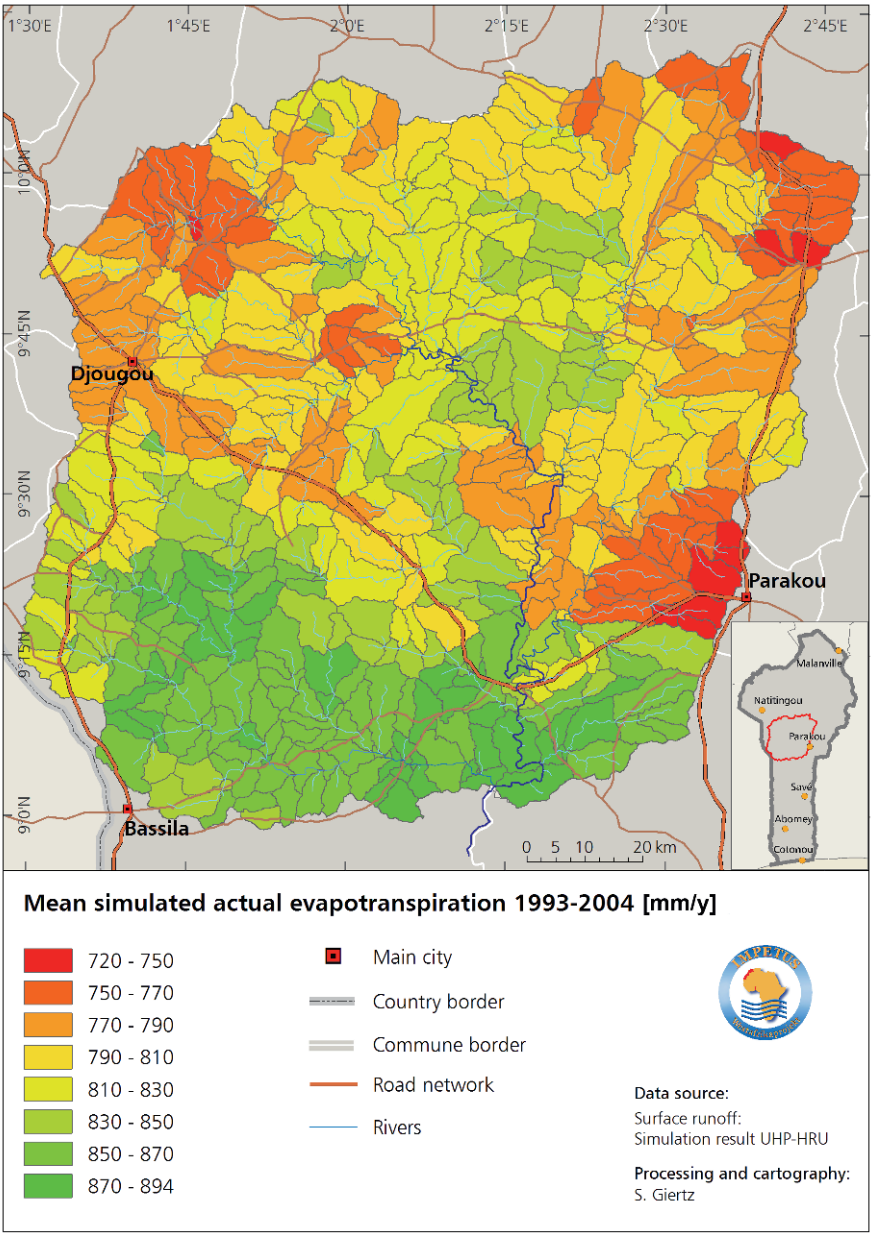

Fig. I-6.1.10: Spatial pattern of actual evapotranspiration in the Upper Ouémé catchment (14,318 km²) for the period 1993-2004 (simulation result UHP-HRU).

ment, receiving nearly the same amount of rainfall in the regarded period. The fraction of simulated actual evapotranspiration and discharge is comparable with the results of Hiepe (2008).

The discharge components reveal the importance of interflow with a fraction of 59-61% of the total discharge. The importance of interflow was also reported for local studies by Giertz (2004). In that study, the interflow ranged from 39 to 67% of the total discharge in the different sub-catchments of the Aguima in the years 2001 and 2002. This result could not be confirmed by Hiepe (2008), who reported only 3-6% for the simulation with the SWAT model. She attributed this to a problem with the representation of interflow in flat regions with SWAT, which has also been reported by other authors (Eckhardt et al. 2002; Sintondji 2005).

The model results of UHP-HRU were used to analyze the spatial patterns of the hydrological processes in the catchment. The pattern of the different hydrological components reflects the spatial pattern of precipitation, land use and soil characteristics. As an example, the mean simulated evapotranspiration and the surface runoff for the period 1993-2004 are shown in figures I-6.1.9 and I-6.1.10. The highest amount of surface runoff was produced in the northwest of the catchment, where cropland is the predominant land use and where the highest precipitation amounts are measured (Fink et al. 2008, see also fig. I-4.2.1). It is clearly visible that in general, high surface runoff amounts occur in a buffer along the roads, where the settlements and the cropland are located. In the central and southern part of the catchment, the surface runoff is relatively low, which can be explained by the large areas of protected forest. This pattern corresponds to the results of Hiepe (2008), who applied the SWAT model for the Upper Ouémé catchment for erosion modeling purposes for the period 1998-2005 (see below). The pattern of the actual evapotranspiration also shows the impact of land use, but the water availability is more strongly influenced by rainfall variability. In the Djougou region, for example, which receives the highest amount of rainfall in the catchment, the evapotranspiration rate is higher than in other regions even though the highest density of cropland is located here.

I-6.1.4 Soil degradation and soil erosion

Despite the flat relief of the country, soil degradation is a considerable problem in Benin. This is because high rainfall intensities and low-input farming systems are prevalent. Soil degradation is aggravated due to a rapid expansion of cropland resulting from population growth. This includes migration, a lack of soil conservation activities and a recent slight increase in the number of strong (> 40 mm per day) rainfall events as a reflection of a decadal-scale recovery from the drier years of the 1970s and 1980s (see fig. I-5.1.4). The traditional fallow farming systems in Benin are only sustainable for long fallow periods of at least 5 to 10 years. Soil fertilization strategies other than crop rotation, including fallowing and the inclu-

sion of nitrogen-fixing groundnut in the crop cycle, are rare in the Upper Ouémé catchment. Mineral fertilizer is only applied to the cotton cash crop and some maize.

The two most important processes that lead to soil degradation are soil erosion and nutrient depletion. Both are closely connected, as the erosion of topsoil implies a loss of soil organic matter and associated nutrients. This leads to subsequent effects such as compaction, crusting, water-logging, and a decrease in biological activity. At the same time, nutrient depletion also enhances soil erosion due to reduced biomass and ground coverage. Both processes can heavily affect agricultural production and food security. The dominant erosion forms in the Upper Ouémé catchment are sheet and rill erosion.

Soils in the Upper Ouémé catchment and their susceptibility to soil degradation

The Upper Ouémé catchment is dominated by ferruginous soils (*sols ferrugineux tropicaux lessivés*), which are classified as Acrisols or Lixisols according to the World Reference Base for Soil Resources (FAO-ISRIC-ISSS 1998). Furthermore, Ferralsols, Plinthosols, Gleysols, Vertisols and close to inselbergs Cambisols and Leptosols occur (Orstom 1976). Ferruginous duricrusts are only widespread in the west of the catchment, on the Djougou plateau and on residual hills. Soil type variations along hillslopes and small-scale variability of soil properties are high. Recent physical and chemical soil properties for representative profiles for all 38 soil types in the Upper Ouémé catchment have been obtained by Sintondji (2005) and Hiepe (2008). Although the soils in the catchment are chemically more fertile than many soils in southern Benin, nutrient availability is often limited, and physical restrictions due to high gravel content and indurated horizons in the subsoil are high.

Except for the Gleysols in the inland valleys, the sandy topsoils on savannah land are not particularly susceptible to erosion. This results in a medium erosion risk (Junge 2004). However, soil erosion risk is significantly higher on cropland and bare soil. Junge (2004) quantified local soil erosion rates for different crops and tillage systems in the Aguima sub-catchment in 2002. She obtained the highest amounts of soil loss from plots with cotton planted in rows in the direction of the slope (runoff 229 mm/y, soil loss 124 t/ha/y) and on plots with yam mounds (168 mm/y runoff, 41 t/ha/y). In contrast, surface runoff and soil loss was much lower in fields with crops planted parallel to the contour lines (e.g., cotton, runoff 106 mm/y, soil loss 13 t/ha/y). On savannah plots, runoff and soil loss were up to 20 times lower. These locally measured erosion rates cannot be directly transferred to the catchment scale, since a major part of the eroded soil is deposited and does not reach the main channel. Nevertheless, such local studies are valuable for comparing different land use and management systems and for interpreting results from erosion modeling at the regional scale.

Modeling soil erosion at the regional scale

To analyze the hydrological and erosional processes in the Upper Ouémé catchment, the model SWAT (Arnold et al. 1993) was applied. The model is semi-distributed, i.e., it takes into account the spatial variability of land use and soils. The model was calibrated simultaneously at the outlets of the intensively agriculturally used Donga-Pont sub-catchment (586 km²) near Djougou and the less agriculturally used Terou-Igbomakoro sub-catchment (2,324 km²) in the southwest of the catchment. This was done using daily discharge measurements for 1998-2001. In the second step, sediment yields were calibrated using daily suspended sedi-

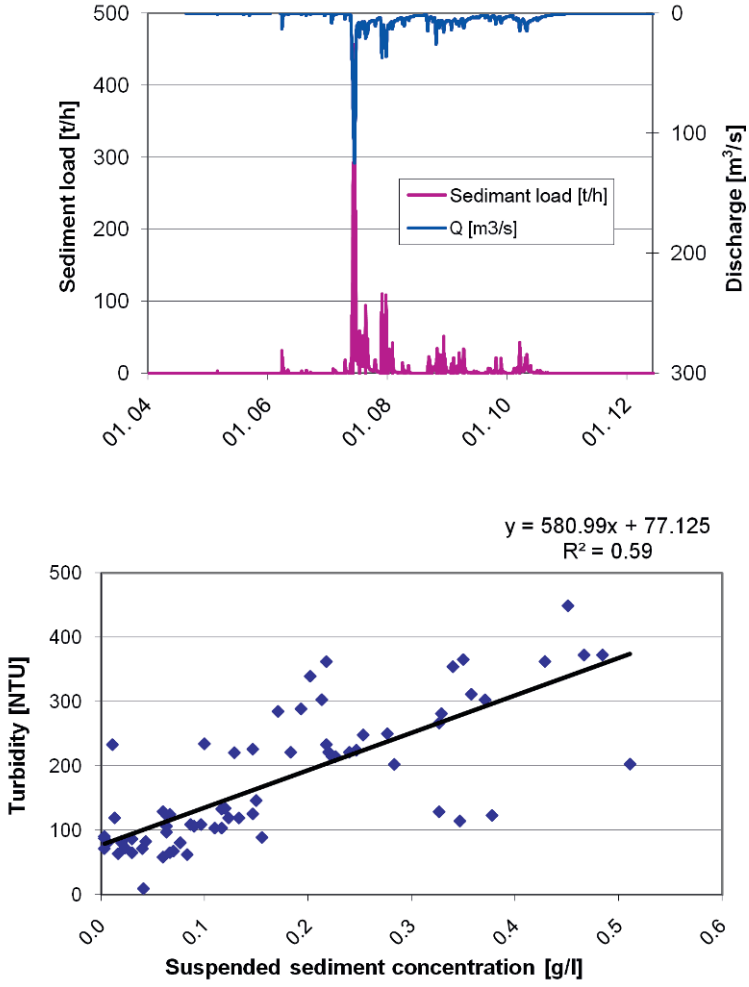

Fig. I-6.1.11: Example of a turbidity: Suspended sediment concentration relationship for the Donga-Pont sub-catchment (587 km²) and the derived hourly sediment load for 2005.

ment concentrations from half-hourly, continuous turbidity measurements in 2004--2005. Moreover, the model was extensively validated for different time periods and sub-catchments. Subsequently, current soil erosion hotspots could be identified.

Measurements of suspended sediment

A calibration and validation of the sediment budget of regional, time-continuous hydrological models (e.g., SWAT) in developing countries is very rare. Existing studies usually stick to a monthly time step and simple discharge-sediment relationships that are often inaccurate due to hysteretic effects. An alternative approach is to use turbidimeters, which continuously measure the turbidity, i.e., the reduction of the transparency of water caused by suspended particles. For this study, three multi-parameter probes, type YSI 600-04, including a turbidity sensor with wipers, automatically recorded turbidity, electrical conductivity, water temperature, and water level every 30 minutes from 2004-2006. For each site, a specific relationship between turbidity and suspended sediment concentration (SSC) was determined through filtration of 69-87 water samples taken after rainfall events (for an example, see fig. I-6.1.11). The coefficients of determination (R^2), ranging from 0.55 and 0.78, were satisfactory, and they lie within the ranges published in the literature for catchments in Germany (Pfannkuche and Schmidt 2003), the United States (Inamdar 2004; Dana et al. 2004), and Nepal (Brasington and Richards 2000).

The derived hourly suspended sediment curves (see fig. I-6.1.11) could be used for weekly and daily calibration of the sediment yield, assuming that the bed load plays a minor role in the catchment. The calculated sediment yields and the maxima of SSC lie in the typical range of reported values for African rivers (e.g., Walling et al. 2001). The measured amounts of suspended sediment at the regional scale are one or two orders of magnitude lower than the soil loss rates of 12-120 t/ha/y in fields and 3.8 t/ha/y in savannah land obtained by Junge (2004) with small erosion plots. This reflects the fact that usually less than 20% of the eroded material reaches the channel in catchments up to 10,000 km^2 (Van Noordwijk et al. 1998).

Model calibration

In the default modus, the SWAT model substantially overestimated runoff and underestimated actual evapotranspiration. Thus, groundwater parameters and the soil evaporation compensation factor (ESCO) were adjusted to correctly represent runoff amounts. The baseflow recession constant was estimated from discharge data at the Donga-Pont and Terou-Igbomakoro outlets using the baseflow filter program from Arnold and Allen (1999). Moreover, soil available water capacity and soil depth were increased to enhance soil percolation and reduce surface runoff. Subsequently, the surface runoff lag coefficient and the groundwater parameters were fine-tuned to visually optimize the agreement of the weekly curves.

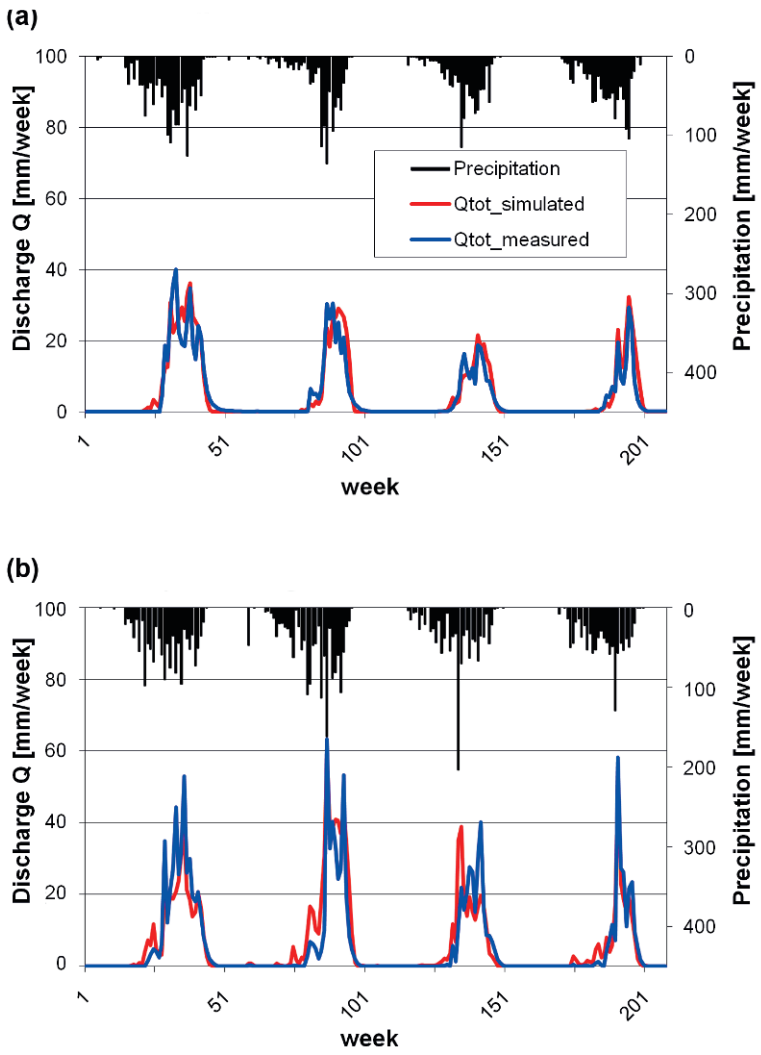

Fig. I-6.1.12: Comparison of measured and simulated weekly discharge for the calibration period: (a) Terou-Igbomakoro (2,323 km²) and (b) Donga-Pont (587 km²) outlets.

As a result of hydrological calibration, yearly, monthly, and weekly total discharge and discharge fractions for 1998-2001 agreed well, as indicated by the measures of performance. These performance measures are, namely, model efficiency, index of agreement (IoA) and the coefficient of determination (R^2) (see weekly curves in fig. I-6.1.12). The beginning and end of the rainy season, as well as most peaks of the hydrograph, were well reproduced. The discharge curve for Terou-Igbomakoro was slightly biased at the end of the rainy season due to a retardation of the baseflow. The mean annual water balance was plausible for the (sub-) catchments as well as for the hydrolo-

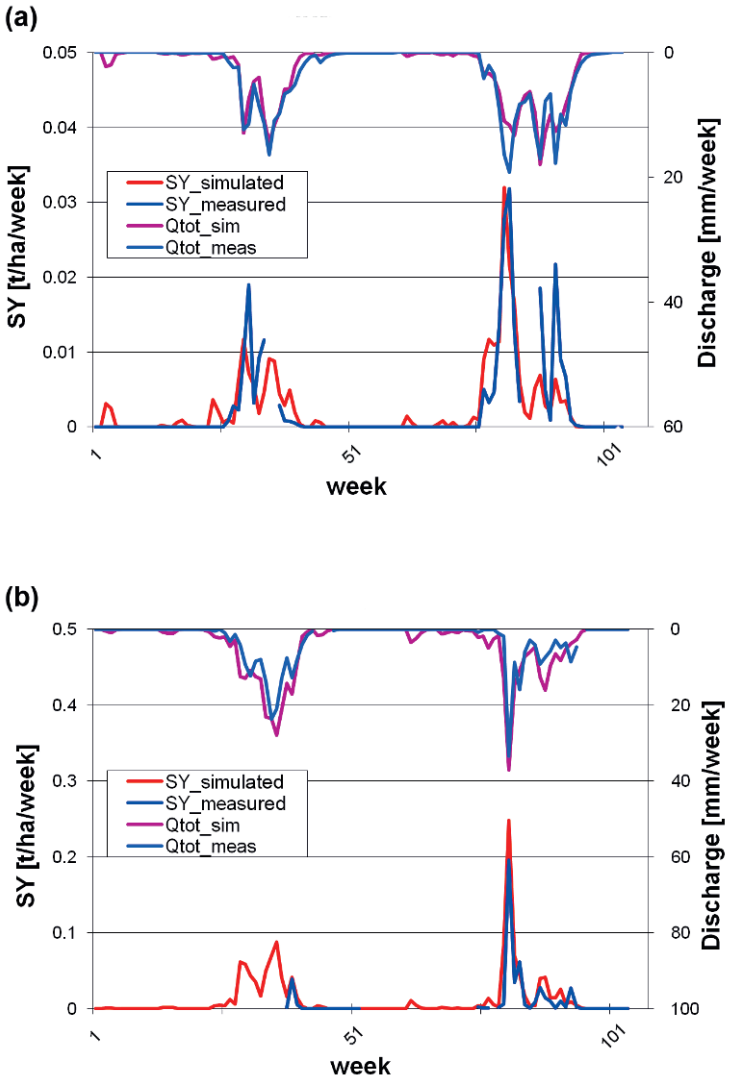

Fig. I-6.1.13: Comparison of measured and simulated weekly sediment yield (SY) for the calibration period: (a) Terou-Igbomakoro (2,323 km²) and (b) Donga-Pont (587 km²) outlets.

gical response units with higher actual evapotranspiration, leaf area index and biomass in forest areas compared to savannah and cropland.

During the subsequent calibration of the sediment budget at the same outlets (see fig. I-6.1.13), the USLE crop practice factor (C-factor) for cropland was reduced from the default value of 0.2 to 0.18 in order to best represent sediment yield derived from the turbidity measurements in 2004/05. Furthermore, the C-factor was slightly increased for inland valleys and woodland and tree savannahs. The factor that determines the maxi-

mum amount of sediment that can be transported in the channel during an event, then, was increased from 0.0001 to 0.0005 to avoid severe transport limitations in the Donga-Pont sub-catchment.

Model validation

The application of the calibrated model to the validation period (2002 to 2005) led to only minor reductions of performance of discharge at the Terou-Igbomakoro and Donga-Pont outlets (see table I-6.1.8).

Total runoff amounts were very well reproduced for the Terou-Igbomakoro sub-catchment. However, it was overestimated by 28% for the Donga-Pont sub-catchment due to two discharge peaks in 2003 and 2005, for which the model overreacts to underlying extreme rainfall amounts of 150-200 m per week (see fig. I-6.1.14). Spatial validation at several other outlets showed satisfactory agreement of measured and simulated discharge (see table I-6.1.8).

Table I-6.1.8: Validation of discharge at several outlets in the Upper Ouémé catchment.

	Catchment area [km²]	Simulation period	Model Efficiency	R^2	IoA	Q_{sim}/Q_{meas} [%]
Donga-Pont	586	2002-2005	0.82	0.84	0.96	111
Donga-Affon	1,308	1998-2005	0.77	0.84	0.78	109
Terou-Igbomakoro	2,324	2002-2005	0.83	0.85	0.96	90
Terou-Wanou	3,136	1998-2002	0.77	0.77	0.70	86
Ouémé-Aval/Sani	3,506	1999-2005	0.47	0.91	0.85	156
Ouémé-Beterou	10,085	1998-2005	0.59	0.89	0.82	146

The validation of the sediment budget at the Ouémé-Beterou outlet achieved satisfactory results for the year 2005. It had an overestimation of the sediment yield by 58%, but a good representation of daily and weekly temporal dynamics. However, in 2004, the simulated sediment yields were substantially higher than the very low measured sediment yields from the daily water samples (which were probably subject to handling errors in the first year). A validation of the sediment budget for 2006 would deliver further insights.

Uncertainties in input and calibration data as well as model assumptions have been analyzed in detail (see Hiepe 2008). Uncertainties could be significantly reduced by improving the accuracy and completeness of the suspended sediment

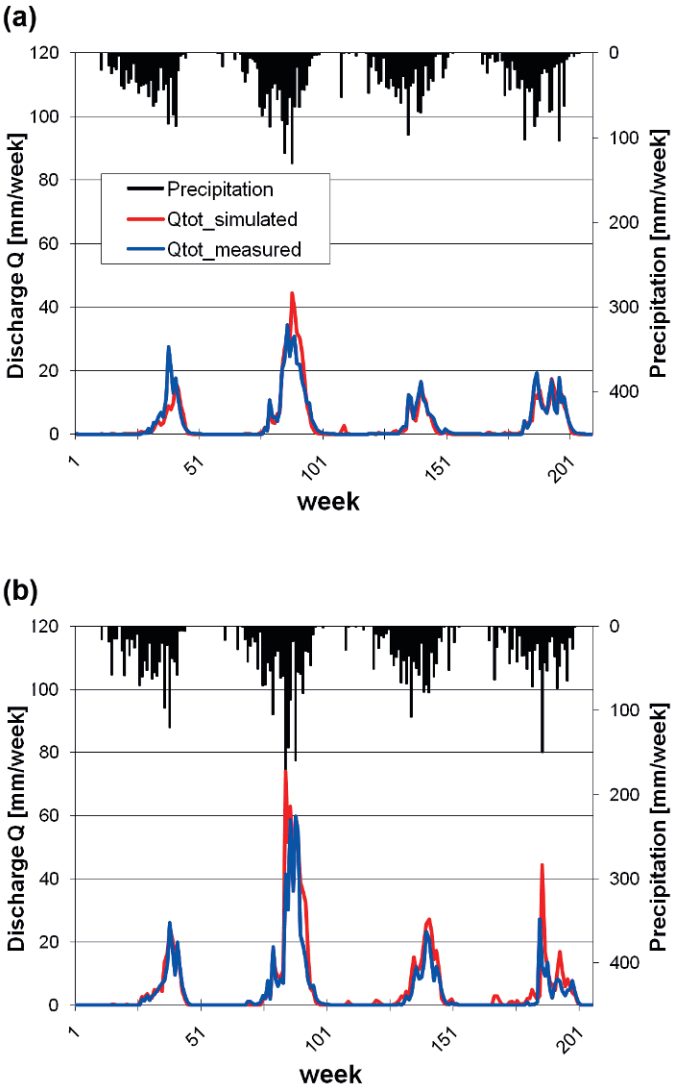

Fig. I-6.1.14: Comparison of measured and simulated weekly discharge for the validation period: (a) Terou-Igbomakoro (2,323 km²) and (b) Donga-Pont (587 km²) outlets.

measurements, the groundwater parameters and the physical soil parameters, to which the model is highly sensitive.

Discussion of model results

After a successful model validation, the model results could be analyzed in space and time. The mean simulated total discharge for the Upper Ouémé catchment in the period 1998-2005 amounts to 219 mm/y with about 107 mm surface runoff per year (see table I-6.1.9). Total discharge and surface runoff are substantially higher in the intensively used Donga-Pont sub-catchment. The mean annual sediment loss of 0.22 t/ha/y in the whole Upper Ouémé catchment lies between the values for the Donga-Pont and the Terou-Igbomakoro sub-catchments. The mean annual sediment yield in the Donga-Pont sub-catchment is about six times higher than that for the Terou-Igbomakoro sub-catchment, reflecting a higher portion of cropland (factor 3.5) and higher rainfall amounts and intensities in this region. The highest sediment yields, with a maximum of 2.21 t/ha/y, were obtained in the sub-basins around Djougou. Sintondji (2005) simulated considerably higher sediment yields of 4.72 t/ha/y for 1998-2003 for the Terou-Igbomakoro sub-catchment without calibrating and validating the sediment budget. The absolute values of the sediment yield presented here seem to be more realistic. However, "real" sediment yields are probably slightly higher due to systematic underestimation in the discharge and sediment data used for calibration during extreme events and the neglect of the bed load.

Cropland is by far the main contributor to the total sediment load in the Upper Ouémé catchment (97%), followed by brush and grass savannah (2.4%) and woodland and tree savannah (0.5%). The average sediment yields for cropland, inland valleys and brush and grass savannah are 2.13 t/ha/y, 0.46 t/ha/y and 0.13 t/ha/y, respectively. The simulated annual sediment yields of 0.06-0.26 t/ha/y for the whole catchment lie within the lower range of values reported in the literature for similar catchments (e.g., Dickinson and Collins 1998; Walling et al. 2001). Rainfall, sediment, and water yield peak in August/September, while suspended sediment concentrations reach a maximum in June/July. In 1998-2005, about 28% of the total rainfall was responsible for 50% of the sediment load.

Table I-6.1.9: Land use distribution, rainfall and mean simulated water yield (WY), surface runoff (Qsurf) and sediment yield (SY) in the Donga-Pont and Terou-Igbomakoro sub-catchments and the Upper Ouémé catchment for 1998-2005.

	Field [%]	Savannah [%]	Forest [%]	Rainfall [mm/y]	WY [mm/y]	Qsurf [mm/y]	SY [t/ha/y]
Donga-Pont	39	61	0	1294 +/- 142	297 +/- 142	174 +/- 78	0.85 +/- 0.47
Terou-Igbomakoro	11	72	17	1157 +/- 170	213 +/- 103	96 +/- 41	0.14 +/- 0.06
Upper Ouémé	14	78	8	1184 +/- 121	219 +/- 68	107 +/- 28	0.22 +/- 0.06

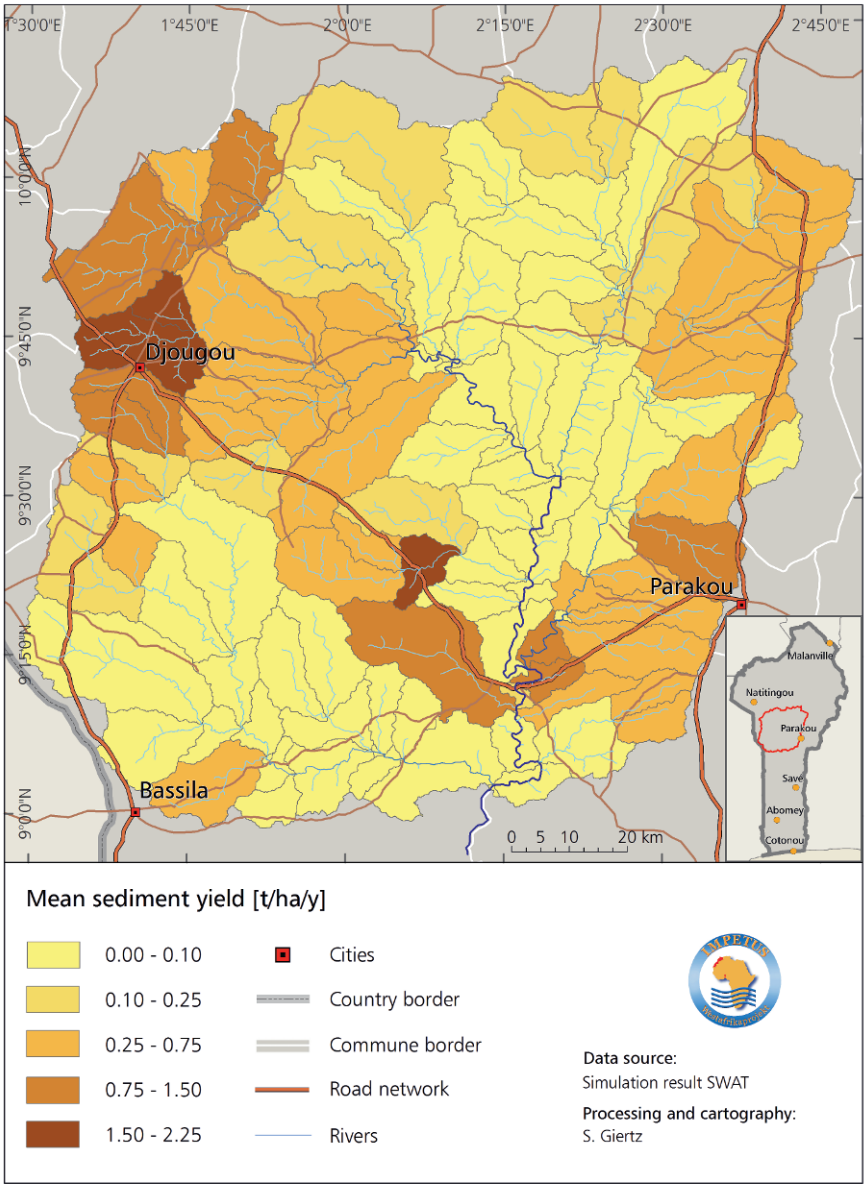

Fig. I-6.1.15: Spatial distribution of the mean simulated sediment yield in the Upper Ouémé catchment (14,318 km²) for the period 1998-2005.

Figure I-6.1.15 shows the spatial pattern of the mean sediment yield for 1998-2005. Current hotspots of soil erosion can be identified in the northwest of the catchment, along the road Djougou-Parakou and on the Parakou plateau. In the northeast of the catchment, sediment yields are also elevated.

The simulated mean sediment yield at the regional scale equals an average topsoil loss of about 0.14 mm per year on cropland. This is about three to five times lower than the local scale rates estimate by Junge (2004) in the Aguima catchment.

I-6.1.5 Conclusions

Concerning hydrology, two different model concepts have been adapted to the conditions of Benin. With the physically based model approach, the process understanding was confirmed. The validation of the conceptual model revealed that it is applicable for the region and is able to reproduce the discharge dynamics and amounts for catchments with different land use as well as for wet and dry periods. Also, the analysis of the spatial pattern shows that the model is able to reproduce differences in hydrological behavior due to differences in land use and climate conditions. Both process understanding and successful modeling is a prerequisite for Global Change scenario analysis, which will be dealt with in part II of this book.

In addition to water balance, sediment budgets were analyzed in the Upper Ouémé valley. The model system SWAT was successfully calibrated and validated. The model was able to reproduce recent water and sediment dynamics satisfactorily, and it performed well under a wide range of conditions, including different land uses and climatic conditions. Current hotspots of soil erosion could be identified, and their existence was verified in the field. This model, then, can be used for scenario analysis (see sect. II-4.2).

References

Arnold JG, Allen PM (1999) Validation of automated methods for estimating baseflow and groundwater recharge from stream flow records. J Am Water Resour As 35(2):411-424

Arnold JG, Allen PM, Bernhardt G (1993) A Comprehensive Surface-Groundwater Flow Model. J Hydrol 142(1-4):47-69

Bormann H (2005) Regional hydrological modelling in Benin (West Africa): Uncertainty issues versus scenarios of expected future environmental change. Phys Chem Earth 30(8-10):472-484

Brasington J, Richards K (2000) Turbidity and suspended sediment dynamics in small catchments in the Nepal Middle Hills. Hydrol Process 14:2559-2574

Dana GL, Panorska AK, Susfalk RB, McGraw D, McKay WA, Dornoo M (2004) Suspended sediment and turbidity patterns in the Middle Truckee River, California for the period 2002-2003. http://www.truckee.dri.edu/tmdl/SedimentPatternsMiddleTruckeeDRI2004.pdf. Accessed 25 August 2009

Dickinson A, Collins R (1998) Predicting Erosion and Sediment Yield at the Catchment Scale. In: de Vries FWTP, Agus F, Kerr J (eds) Soil erosion at multiple scales. Principles and methods for assessing causes and impacts. CABI Publishing, Wallingford

Diekkrüger B, Arning M (1995) Simulation of water fluxes using different methods for estimating soil parameters. Ecol Model 81:83-95

Eckhardt K, Haverkamp S, Fohrer N, Frede H-G (2002) SWAT-G, a version of SWAT99.2 modified for application to low mountain range catchments. Phys Chem Earth 27:641-644

FAO-ISRIC-ISSS (1998) World Reference Base for Soil Resources. World Soil Resources Reports 84. FAO, Rome. http://www.fao.org/docrep/W8594E/W8594E00.htm.
Accessed 25 August 2009

Faß T (2004) Hydrogeologie im Aguima-Einzugsgebiet in Benin, Westafrika. Doctoral Thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/ fass_thorsten.
Accessed 24 August 2009

Feddes RA, Kowalik PJ, Zaradny, H (1978) Simulation of field water use and crop yield. Simulation Monograph. Pudoc, Wageningen

Fink AH, Pohle S, Hoffmann R (2008) Spatial and Temporal Rainfall Climatologies of Benin. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 21-22. Department of Geography, University of Bonn, Bonn

Garbrecht J, Martz LW (1997) TOPAZ: An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterisation. TOPAZ user manual. U.S. Department of Agriculture, ARS Publication GRL 97 (4), El Reno, OK

Giertz S (2004) Analyse der hydrologischen Prozesse in den sub-humiden Tropen Westafrikas unter besonderer Berücksichtigung der Landnutzung am Beispiel des Aguima-Einzugsgebietes in Benin. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.unibonn.de/diss_online/math_nat_fak/2004/giertz_simone.
Accessed 25 August 2009

Giertz S (2008) Gauged Sub-Catchments of the Ouémé River. In: Judex M, Thamm H-P (eds) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 29-30. Department of Geography, University of Bonn, Bonn

Giertz S, Diekkrüger B, Steup G (2006a) Physically-based modelling of hydrological processes in a tropical headwater catchment in Benin (West Africa) - process representation and multicriteria validation. Hydrol Earth Syst Sc 10:829-847

Giertz S, Diekkrüger B, Jaeger A, Schopp M (2006b) An interdisciplinary scenario analysis to assess the water availability and water consumption in the Upper Ouémé catchment in Benin. Adv Geosci 9:3-13

Giertz S, Diekkrüger B (2006c) Evaluation of three different model concepts to simulate the Rainfall-runoff process in a tropical headwater catchment in West Africa. Geo Öko 27:117-147

Giertz S, Junge B, Diekkrüger B (2005) Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. Phys Chem Earth, Parts A/B/C, 30(8-10):485-496

Götzinger J (2007) Distributed Conceptual Hydrological Modelling - Simulation of Climate, Land Use Change Impact and Uncertainty Analysis. Mitteilungen Institut für Wasserbau, Universität Stuttgart 164.
http://elib.uni-stuttgart.de/opus/volltexte/2007/3349/pdf/ Diss_Goetzinger_ub.pdf.
Accessed 25 August 2009

Hiepe C (2008) Soil degradation by water erosion in a sub-humid West-African catchment a modelling approach considering land use and climate change in Benin. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/ hiepe_claudia.
Accessed 25 August 2009

Inamdar S (2004) Assessment of modelling tools and data needs for developing the sediment portion of the TMDL plan for a mixed landuse watershed. Great Lakes Centre, Buffalo http://www.glc.org/basin/pubs/projects/ny_AsModTl_%20pub1.pdf. Accessed 25 August 2009

Judex M (2008) Modellierung der Landnutzungsdynamik in Zentralbenin mit dem XULU Framework. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/judex_michael. Accessed 25 August 2009

Junge B (2004) Die Böden des oberen Ouémé-Einzugsgebietes in Benin/Westafrika - Pedologie, Klassifizierung, Nutzung und Degradierung. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2004/Junge_birte. Accessed 25 August 2009

Kamagate B, Favreau G, Séguis L, Seidel JL, Descloitres M, Affaton P (2007) Hydrological processes and water balance of a tropical crystalline bedrock catchment in Benin (Donga, upper Ouémé River). Compte Rendus Académie des Sciences, Volume 339 - Numéro 6:418

Orstom (1976): Carte Pédologique de Reconnaissance à 1: 200,000. Sheets Djougou, Parakou, Save, Abomey

Penman H L (1956) Evaporation: An introduction survey. Neth J Agr Sci 4:8-29

Pfannkuche J, Schmidt A (2003) Determination of suspended particulate matter concentration from turbidity measurements: particle size effects and calibration procedures. Hydrol Process 17:1951-1963

Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. Mon Weather Rev 100:82-92

Ritchie JT (1972) A model for predicting evaporation from a row crop with incompletet cover. Water Resour Res 8:1204-1213

SCS (1972) Estimation of direct runoff from storm rainfall. National engineering handbook, section 4 – hydrology, USDA: 10.1-10.24

Sintondji L (2005) Modelling the rainfall-runoff process in the Upper Quémé catchment area (Terou) in a context of climate change: extrapolation from the local to the regional scale. Doctoral thesis, University of Bonn, Bonn

Smith RE, Parlange J-Y (1978) A parameter-efficient hydrologic infiltration model. Water Resour Res 14:533-538

Sonneveld, BGJS (1997) Dominant Soils of Nigeria. Stichting Onderzoek Wereldvoedselvoorziening van de Vrije Universiteit (SOWVU), Amsterdam.

Turc L (1963) Evaluation des besoins en eau d'irrigation, évapotranspiration potentielle, formulation simplifié et mise à jour. Ann Agron 12:13-49

Varado N, Braud I, Galle S, Le Lay M, Séguis M, Kamagate M, Depraetere M (2006) Multicriteria assessment of the Representative Elementary Watershed approach on the Donga catchment (Benin) using a downward approach of model complexity. Hydrol Earth Syst Sc 10:427-442

Van Noordwijk M, van Roode N, McCallie EL, Lusiana B (1998) Erosion and Sedimentation as Multiscale, Fractal Processes: Implications for Models, Experiments and the Real World. In: de Vries FWTP, Agus F, Kerr J (eds) Soil erosion at multiple scales. Principles and methods for assessing causes and impacts, pp. 223-254. CABI Publishing, Wallingford

Walling DE, Collins AL, Sichingabula HM, Leeks GJL (2001) Integrated assessment of catchment suspended sediment budgets: A Zambian example. Land Degrad Dev 12:387-415

I-6.2 Hydrological processes and soil degradation in Southern Morocco

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Abstract

Hydrological processes in arid and semi-arid catchments like the Drâa valley are driven by rare but often intensive rainfall events, which cause soil erosion by water. Rainfall, temperature and, therefore, hydrological processes in the Drâa valley show a distinct gradient from the south to the north following an increase in altitude. Snow storage in the High Atlas Mountains is important for reservoir filling and, therefore, a simulation and monitoring tool has been developed that is able to quantify snowmelt runoff. Additionally, the model system SWAT (Soil and Water Assessment Tool) has been used to quantify the hydrological processes in the Upper Drâa valley (about 15,000 km^2), which drains into the Mansour Eddahbi reservoir. The oases upstream of the reservoir are considered the most important water users. The results show that the model is able to simulate dry as well as wet periods with reasonable accuracy and can therefore be used for analyzing scenarios of future development.

The oases downstream of the reservoir depend on water release from the reservoir and groundwater availability. Hydro-geological analysis shows that the chain of aquifers below the oases are mainly replenished by stream losses during water release and continuous regional groundwater recharge. Groundwater pumping for irrigation represents the most important consumption. With decreasing water availability from the reservoir, the aquifers are depleted and soil as well as groundwater salinity increases. Measurements and simulations show an increase in salinity with increasing distance from the Mansour Eddahbi reservoir, which is due to enrichment of the aquifers with salts.

Soil erosion in the valley affects soil quality and soil fertility at the local scale, but it also causes siltation in the reservoir. The model system PESERA (Pan European Soil Erosion Risk Assessment) was used to study the risk of soil erosion by water in the Upper and Middle Drâa basin (about 30,000 km^2). Although calibration at the local scale was not possible due to missing field data, the application of PESERA showed a distinct and plausible pattern of soil erosion risks in the basin that could be validated using indirect measures such as vegetation coverage, soil distribution, and reservoir siltation.

Keywords: Hydrological processes, semi-arid, high mountain, snow dynamics, sublimation, snowmelt runoff, stream-aquifer-interactions, groundwater extraction, soil erosion, reservoir siltation, reservoir management, remote sensing, conceptual models, modeling

I-6.2.1 Introduction

In this chapter, the hydrological processes within the Drâa valley are described and quantified using simulation models. The Drâa drains the High Atlas, which consists of summits of up to 4,071 m asl (Jebel M'Goun). The Mansour Eddahbi reservoir represents a distinct separation of the Upper and Middle Drâa valley (see fig. I-3.2.3). The former is drained by the *Oueds* Dadès, Ouarzazate and Ait Douchène (*Oued* is the local term for wadi) while the Middle Drâa valley is drained by the eponymous *Oued* Drâa. The Drâa starts at the outlet of the reservoir and flows directly through the Antiatlas range. It reaches Lake Iriki in the Saharan foreland after a distance of more than 200 km downstream of the reservoir. Since 1972, the stream flow of the *Oued* Drâa has been regulated by the management of the Mansour Eddahbi reservoir (see fig. I-3.2.3).

Four types of rivers can be distinguished in the region: perennial, periodic, episodic, and regulated. The reservoir's eastern tributaries, the Dadès (gauge Ait Mouted) and the M'Goun (gauge Ifre; see fig. I-3.2.3), are perennial. Most of the riparian oases can be irrigated throughout the year using surface water. Hence, the majority of irrigated areas within the catchment are located at these rivers (perimeters of M'Semrir, Boumalne Dadès, Kelaat MGouna, Skoura; see fig. I-3.2.3). Only the oases of Toundout and Skoura are situated at the ephemeral *Oued* Hajjaj north of the Dadès. Furthermore, the surplus of water results in a discharge into the Mansour Eddahbi reservoir (gauge Tinouar). Only prolonged droughts over several years are capable of interrupting this reliable contribution. The western tributaries Mellah (gauge Agouillal), Iriri (gauge Tamdroust) and *Oued* Ouarzazate (gauge Amane-n-Tini) drain sub-catchments that are less elevated or have less favorable aquifer conditions. Therefore, the discharge is absent during summertime, forcing riparians to rely on groundwater for irrigation. The Ouarzazate oasis is located at the *Oued* Ouarzazate's outlet into the reservoir. The southwestern tributary, Ait Douchène (gauge Assaka), drains the Basin of Tazenakht, which is under a more strongly arid influence. Runoff occurs infrequently, and the Ait Douchène is therefore classified as an episodic river. Irrigation is carried out using groundwater predominantly from the alluvial aquifers. Figure I-6.2.1 gives mean monthly runoff diagrams measured at the named gauges. The Middle Drâa valley faces arid to hyper-arid conditions and the discharge here is regulated by the reservoir. Husbandry relies on irrigation by surface water from the upstream reservoir and on individually pumped groundwater. Agricultural production, and thus the main water consumption, is concentrated on the six Drâa oases Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua and M'hamid (see fig. I-3.2.3). Additionally, agricultural activity occurs along the tributaries of the *Oued* Drâa and locally within sedimentary basins adjacent to the *Oued* Drâa (Feijas).

In arid to semi-arid environments, evapotranspiration is the dominant factor in the water balance. The soil water dynamic is influenced by high rock contents and shallow soils, favoring infiltration excess runoff. On the other hand, epheme-

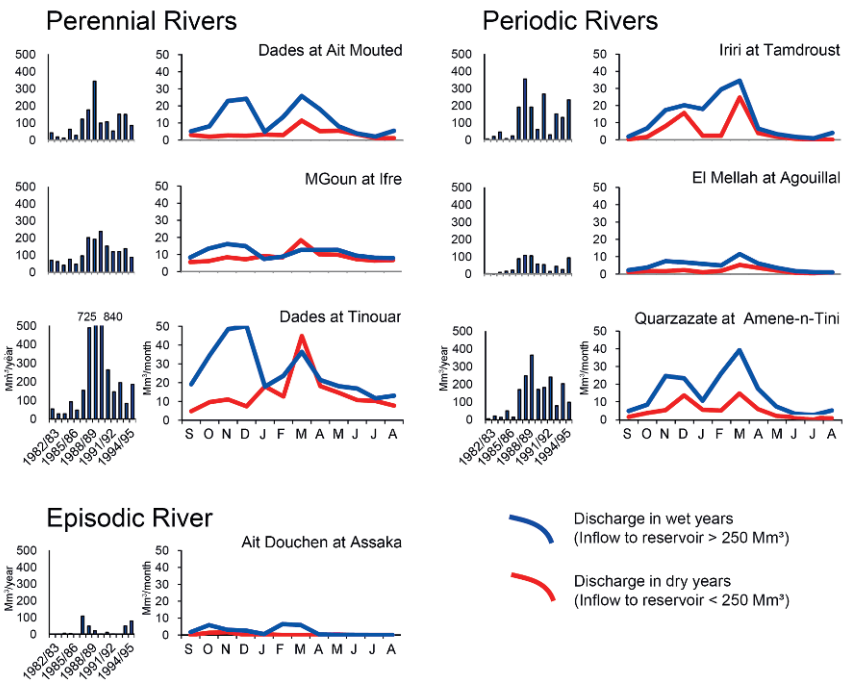

Fig. I-6.2.1: Mean annual discharge of different tributaries to the Mansour Eddahbi Reservoir (1982-1996).

ral channel beds are characterized by high infiltration rates and therefore constitute the major recharge areas. These processes have been analyzed at the local scale (see subsect. I-6.2.3). At the regional scale, hydrological processes, such as infiltration or groundwater recharge, vary strongly according to the topographic and climatic boundary conditions. Regional models are applied to quantify water fluxes within the different subsystems (see subsect. I-6.2.3).

Flood discharge in the mountains is rare, extreme, and highly variable, depending on snowmelt and precipitation. Snow from the "water towers" of the High Atlas Mountains is a major source for freshwater renewal and for water availability in the arid lowlands. The mountain valleys as well as the foreland basins depend on the irrigation water provided by snow-fed rivers. The temporal dynamics of snow cover as well as losses due to sublimation will be discussed in subsection I-6.2.2.

In addition to surface water availability, different aquifer systems contribute to the discharge in the Upper Drâa valley. Jurassic limestone aquifers in the elevated areas of the northeastern catchment are mainly recharged by the wadis, and they deliver a reliable base flow throughout the year. Hydrostratigraphy controls the resident time and the springs and is therefore important for the temporal dynamics of the discharge. In the basin, the discharge generated within the mountains is routed, enabling irrigation in the riparian oases. Local discharge is generated only du-

ring occasional severe rainfall events. These events occur infrequently and are erratic, but they are essential to the operation of the downstream reservoir. The quantification of different affluxes to the reservoir and the relative importance of the subsystems will be discussed in subsection I-6.2.3. Due to the importance of snowfall and storm events, this section will focus on surface water-related processes.

As pointed out previously, groundwater is of increasing importance in the Middle Drâa valley. The groundwater system of the Middle Drâa valley is strongly linked to the hydrological regime due to pronounced stream flow-aquifer interactions, though lateral affluxes contribute to the alluvial aquifers as well (see subsect. I-6.2.4).

Deterioration in soil quality takes place in many oases, where use of groundwater for irrigation purposes without proper soil amelioration is common. Soils and groundwater are prone to salinization. Increased sodium content causes yield losses and can lead to structural instability of the soil and an endangered drinking water supply (see subsect. I-6.2.5).

The assessment of the water cycle in terms of water availability already stresses the importance of natural resources for producing agricultural goods. Beyond water, soil is a limited resource. Soil erosion poses a serious threat to pastoralists by promoting desertification (e.g., Le Houérou 1996) and to hydro-engineers by reducing the reservoir's volume (Lahlou 1988; see subsect. I-6.2.6).

I-6.2.2 Seasonal predictions of snowmelt in the High Atlas mountains for reservoir management

Mountains play an important role in the regional water balance of large, complex, semi-arid basins (Pitlick 1994; Flerchinger and Cooley 2000; Salvetti et al. 2002; Khazaei et al. 2003; Viviroli et al. 2003). However, the contribution of snow and rainfall to the annual and multi-annual water balance in remote high mountain regions in northwestern Africa is largely unknown (Matthews 1989). In Morocco, however, the uneven and erratic nature of rain and snowfall in addition to large evaporation losses, especially in the High Atlas Mountains, causes major water management problems (World Bank 1994).

Therefore, snow research and hydrological modeling in Morocco is of increasing interest to water management institutions. Snow from the "water towers" of the High Atlas Mountains is a major source for freshwater renewal and for water availability in the arid lowlands of southeastern Morocco. After dry winters with limited snowfall and rainfall, the actual storage of the dam decreases in summer to a minimum of 20% of its capacity. This reveals the importance of the snow cover for the basic water supply of the foreland.

Snowfall in the High Atlas Mountains usually occurs from October to May, but the snow cover is rarely continuous (Youbi 1990). Snow ablation in the highly elevated semi-arid environments of the study area is characterized by two import-

ant processes: snowmelt and sublimation. In general, sublimation takes place where cold and dry climatic conditions exist. Visible signs of enhanced evaporation are snowy spikes, commonly called penitents. They indicate the initial snow level, and they seem to rise out of the snow cover while it is carved between the spikes during snow ablation. On the M'Goun range summits, snow penitents have been observed, indicating stable climatic conditions favorable for sublimation over several weeks. Sublimating snow is withdrawn from the local hydrological system, which is usually not considered in water balance estimations.

To cope with the snow dynamics, the snow cover was analyzed in space and time in a multi-level approach. This approach includes ground-based observations of snow and weather characteristics as well as remote sensing and snowmelt modeling.

Accordingly, the aims of snow research within the IMPETUS Morocco project are:

1) to monitor and model snowfall and ablation through automatic weather stations, additional field experiments, and detailed physical modeling at the point scale,

2) to extrapolate measurements and modeling results from the point to the regional scale and to model snowmelt runoff with a conceptual model at the basin scale,

3) to investigate the snow cover and its contribution to the regional water balance by extending the basin scale model to the nine sub-basins of the semi-arid Upper Drâa basin using remote sensing and extrapolation techniques.

Snow-related processes at the local scale

Some snow parameters are measured automatically at the climate stations on the mountainous project test sites (see sect. I-4.2). These measurements include snow depth at all four stations above 2,000 m asl and snow pack and snow surface temperatures at the three highest stations. Additionally, the M'Goun station at 3,850 m asl provides data about snow albedo. All of these observations are automatically executed every five minutes throughout the year, although snow is only present for a few months. Together with rainfall, wind speed and direction, air temperature and humidity, and global and net radiation, the data serve as inputs for the physical snow ablation model UEB (Utah Energy Balance Model; Tarboton and Luce 1996).

As rain gauges are not heated, and therefore not able to register snow amounts, the snow depth measurements were carried out automatically. To estimate the total precipitation sum at the test sites, snow depth data were transformed to snow water equivalents using occasional measurements of the snow density and snow water equivalents with snow pillows. A correlation between altitude and mean total annual precipitation sum has been established for regionalization of local scale measurement. Based on this relationship, a precipitation map was calculated using the DEM (Digital Elevation model) of the Drâa basin (see sect. I-4.3). Figure

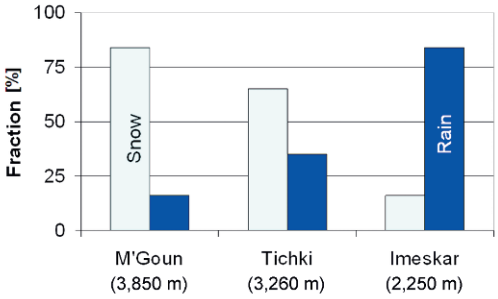

Fig. I-6.2.2: Proportions of snow and rain in total precipitation at three IMPETUS stations (2001-2005) (for the location of the climate stations cf. chap. 4).

I-6.2.2 shows the average proportion of snow and rain at three climate stations. The fraction of precipitation that falls as snow varies from less than 20% to more than 80% at the IMPETUS test sites in the M'Goun region (Schulz and de Jong 2004; Schulz 2006). At the Taoujgalt station (1,870 m asl), snow plays only a minor role in water yield (10% of precipitation sum), and at lower altitudes, snow only occurs as a thin layer for individual days.

Since snow penitents have been observed in altitudes above 3,000 m asl, the role of snow sublimation in the regional water cycle has been analyzed. Snow pans filled with snow were lowered into the snow layer on an altitudinal profile between 2,000 and 3,900 m asl with varying slope aspects at Jebel M'Goun. The results of the snow pan weight measurements, for a snow cover period of some weeks, demonstrated that for altitudes above 3,000 m asl, between 10 and 90% (depending on rising altitude) of the snow water equivalent was sublimated, with secondary modifications due to the slope aspect (Schulz 2006). This underlines the importance of sublimation for water yield at higher elevations, where air temperatures and humidity are low during winter periods and global radiation and wind speed are moderate to high.

Summing up the observations at the mountain test sites of the project's climate monitoring network, the snow cover at the middle elevations (2,000-3,000 m asl) is short-lived due to high melting rates. In the zone above 3,000 m asl, sublimation reduces the water equivalent of snow significantly during winter, before the snow melt occurs.

Simulation of snow dynamics at the local scale

At the point scale, the physically based snow model 'UEB Utah Energy Balance Model' (Tarboton and Luce 1996) was chosen. It calculates the local energy balance and considers melt and sublimation in detail. A number of input data are necessary for the model, including air temperature and humidity, wind speed and global radiation. The data are provided by measurements at the IMPETUS automatic weather stations. Some local site parameters have to be known or estimated, such as the initial water equivalent of the snow pack, average snow density, snow and soil energy conductance and capacity, snow albedo change with time, surface roughness and others. Since some of these parameters were object to model calibration, a sensitivity analysis took place considering the length of the ablation pe-

riod and the proportion of melt and sublimation. The parameters analyzed were surface roughness, energy conductance of the snow surface layer and snow density. Parameter values were changed in the range of ±20%. The effect on the modeled length of the ablation period was between 0 and 5%, where the maximum was reached by a 20% change in snow density. The proportion of melt and sublimation was altered in the range of 5 to 17%, mainly influenced by a change in the surface roughness parameter (Schulz 2006).

Model calibration was done by starting with standard values of the UEB model (pre-calibration; Tarboton and Luce 1996) and by altering the parameter values in the range of literature information and with respect to the local environmental conditions. As mentioned above, the target of the modeling was to reach the day of total ablation (length of the ablation period) and to trace the dynamics of measured daily ablation in total and in proportion to melt and sublimation. The UEB was calibrated for one ablation period at the Tounza station. It was validated with another ablation period and additional data from the Tichki station and from field work. The additional data included snow surface temperatures and snow sublimation measurements. The model validation shows a good agreement of modeled and measured snow surface temperature. The daily ablation amount was validated by snow pillow measurements at the Tounza and Tichki stations (see fig. I-6.2.3). The statistical comparison shows a good agreement between measured and mode-

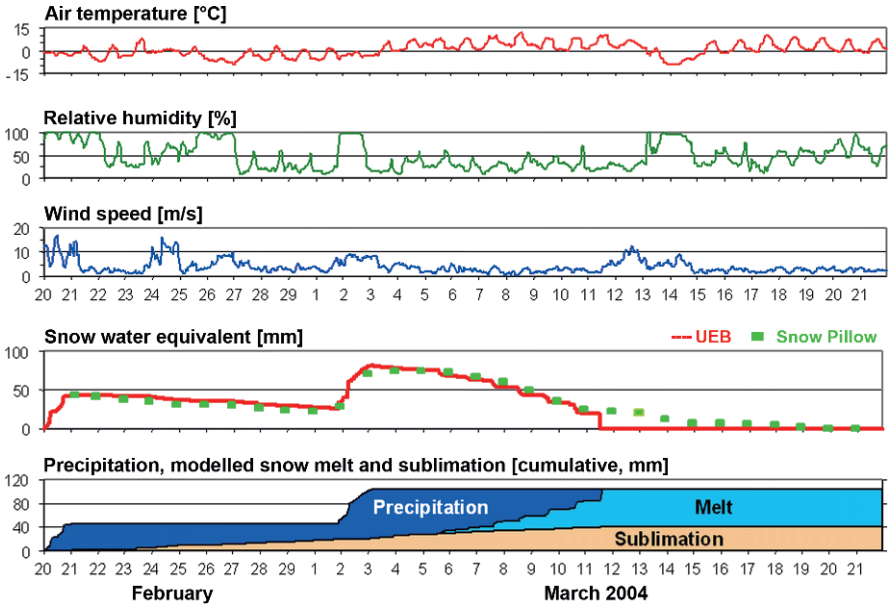

Fig. I-6.2.3: Measurements at the Tounza station (weather data from the automatic weather station, snow water equivalent calculated from snow weight on a snow pillow) and UEB-modelled snow ablation processes (melt and sublimation; precipitation was measured).

led snow ablation (Pearson correlation coefficient: 0.96; coefficient of model efficiency: 0.96). The range of modeled daily rates of melt and sublimation compares well with independent snow pan measurements during a different ablation period (Schulz 2006). For other modeled periods, compare Schulz and de Jong (2004).

Physical snow ablation modeling with the UEB model at the Tounza and Tichki stations confirms that up to 40% of the winter snow water equivalent at around 3,000 m asl is lost due to sublimation. For summits at altitudes up to 4,000 m asl, lower temperatures retard melting, which is the prerequisite for longer sublimation periods during winter. The observed sublimation rate of 2-3 mm per day is able to reduce a snow pack of 50 mm of snow water equivalent within a month, assuming favorable conditions (high insolation, low atmospheric humidity, moderate to high wind speed, and air temperature below and slightly above the freezing point).

With rising temperatures, snowmelt dominates in all altitudes. Below 3,000 m asl, temperatures return to positive values within days after a winter snow storm. This favors melt and leads to infiltration into the mostly unfrozen ground. The overall water loss by sublimation for the entire Upper Drâa basin was modeled at a magnitude of 5 mm, which is about 20% of the annual snow precipitation (26 mm) averaged over the entire basin (see subsect. I-6.2.3).

Remote sensing of snow

For mapping the spatio-temporal dynamic of the snow cover, TERRA-MODIS (Moderate Resolution Imaging Spectroradiometer) satellite image products (MOD09 GHK) were analyzed. With a medium spatial resolution (463 m), but high temporal resolution (nominal 1 day), the sensor is programmed to register the regional snow cover conditions of several snowfall and snowmelt cycles during winter. The Normalized Difference Snow Index (NDSI) classification method was applied to a time series of 500 images (about 100 for each snow cover period for the years 2001 to 2006, lasting from October/November to May/June). The derived snow coverage indicated a minimum duration since the snow cover in-between two images was supposed to be uninterrupted if the snow was present in both images. If not, the snow cover was counted only for the day with observed snow.

The snow classification results based on MODIS images have been calibrated and validated with the IMPETUS climate station records, ground measurements using soil temperature dataloggers distributed on the slopes of the Jebel M'Goun mountain chain, and with the classification results of Landsat and Aster satellite images. Figure I-6.2.4 shows mean values of annual snow cover duration for the Central High Atlas regions belonging to the Drâa basin in recent years (2001-2006). It provides basic information for a variety of environmental applications (modeling in hydrology, meteorology, and botany).

Analysis of the regional characteristics of snow cover shows that below 2,000 m asl, snow cover is only present for single days per year (see fig. I-6.2.5, left). The annual variability of snow cover days is below 20% in altitudes above

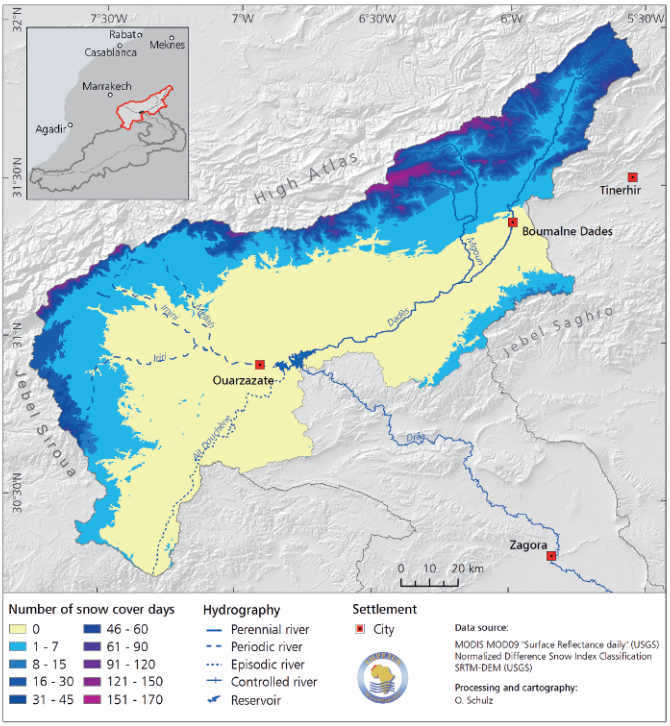

Fig. I-6.2.4: Mean annual snow cover duration for the years 2001 – 2006 in the Upper Drâa basin (Central High Atlas Mountains).

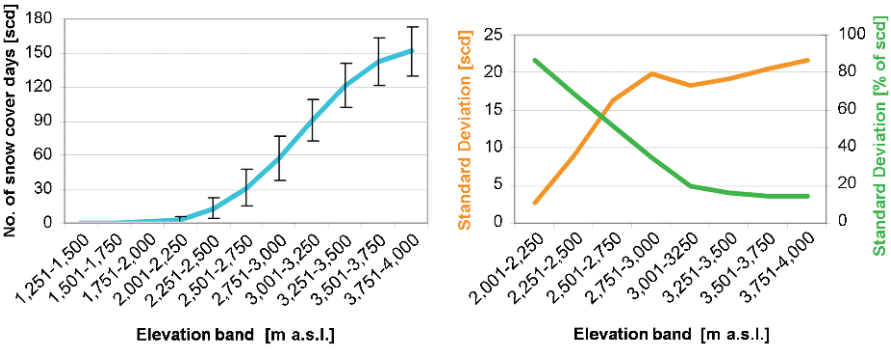

Fig. I-6.2.5: left: Mean snow cover duration and its temporal standard deviation (2001-2006) in the Upper Drâa basin (elevation bands of all sub basins). Right: Temporal standard deviation of snow cover duration (2001-2006) in days and in fraction of the snow cover period for the Upper Drâa basin (elevation bands of all sub basins; scd = snow cover days).

3,000 m asl, but it rises while descending to the Ouarzazate basin. The right side of figure I-6.2.5 shows the standard deviation of snow cover days as a percentage for the years 2001 to 2006.

From the local to the regional scale

While at the local scale, detailed measurements and physical modeling allow the consideration of different snow processes. At the basin and regional scales, such measurements are not available for feeding parameter intensive models. Therefore, local observations are extrapolated to the basin scale using simple approaches such as calculating temperature and precipitation gradients with altitude to represent the most important climatic factors.

For regional modeling, the conceptual SRM Snowmelt Runoff Model (Martinec 1975; Martinec et al. 1998) was first applied to the mountainous river basin of the Upper M'Goun (1,500 km²). In a second step, the model was applied to the other eight sub basins of the Upper Drâa (15,000 km²). Based on a degree-day approach, daily snowmelt in different elevation zones and the subsequent river discharge can be calculated from air temperature, precipitation and snow cover area. SRM model parameters have been adjusted to fit the main observed data and the physically based modeling results. Low runoff coefficients of snow and rain represent the karstic environment, the generally high evaporation rates and the sublimation process in the High Atlas Mountains.

The Java version of SRM (kindly provided by H. Kleindienst; Kleindienst et al. 1999) is part of the monitoring tool PRO-RES (*PROnostic de la fonte de neige pour un REServoir*; PROgnosis of snowmelt runoff for a REServoir). This is used for seasonal snowmelt runoff forecasts. PRO-RES was developed within the IMPETUS SDSS framework and was coupled with a satellite image pre-processor for Terra MODIS image products and the climate and discharge database. With PRO-RES, it was possible to model longer time periods of several years and to route and combine the discharge of all nine sub basins to simulate the overall inflow to the Mansour Eddahbi reservoir at the outlet of the Upper Drâa basin (see fig. I-3.2.3).

The data used in PRO-RES were provided by the regional water service (*Service Eau de Ouarzazate*, in the meantime, ABH *Agence du Bassin Hydraulique Souss-Massa-Drâa*), by the IMPETUS climatological network and by MODIS satellite image products. Since the project measurements began in 2000/01 and MODIS has been operational since 2000, the simulation periods start in 2001. The SRM model was initially calibrated for a single basin (Upper M'Goun) since the discharge measurements at the official hydrological stations in the Drâa basin are uncertain. This is due to the inadequacy of the technical equipment and maintenance for *wadi* river basins, both in periods of very low discharge and during floods.

Only two stations, Ifre and Ait Mouted, are located at rivers with perennial discharges (M'Goun and Dadès). The others experience discharge only episodical-

ly. Taking into account the changes of the river bed, sand intrusion into the gauges and canalizing apart from the gauges, the records of stations at episodic rivers were not included in the calibration process. Even measurements of river discharge at the two perennial stations carry a high degree of uncertainty. Calibration results over a couple of years were moderately successful, as were the results for the consecutive validation periods.

Within PRO-RES, the emphasis was set to match the inflow to the Mansour Eddahbi reservoir near Ouarzazate, including all tributaries of the Upper Drâa. Attention had to be drawn to runoff processes that are not included in the SRM but are necessary for the quantification of the reservoir inflow. This is because there are water losses mainly occurring along the courses of the rivers in the form of channel losses and extractions for irrigation purposes. Both processes are treated with a very simple approach: for all tributaries, monthly constant values of water losses as percentage of river discharge were assumed. PRO-RES was then calibrated again as a whole by adjusting previously uncalibrated SRM parameters for the wadis of the sub basins and water losses for all tributaries during channel routing. Similar to the SRM, calibration for the PRO-RES was done for the first three years of the overall simulation period, and validation was done for the last three years (see fig. I-6.2.6).

The final step in preparing PRO-RES was to calculate the filling level of the reservoir. This had to take into account water losses by evaporation of the lake surface and by water releases (‘*lâchers*’) for irrigation of the downstream oases of the Middle Drâa valley. While the volume of the water releases is calculated and published by the local water service (*Service Eau de Ouarzazate*), evaporation is estimated by this authority based on the area of the water surface according to the

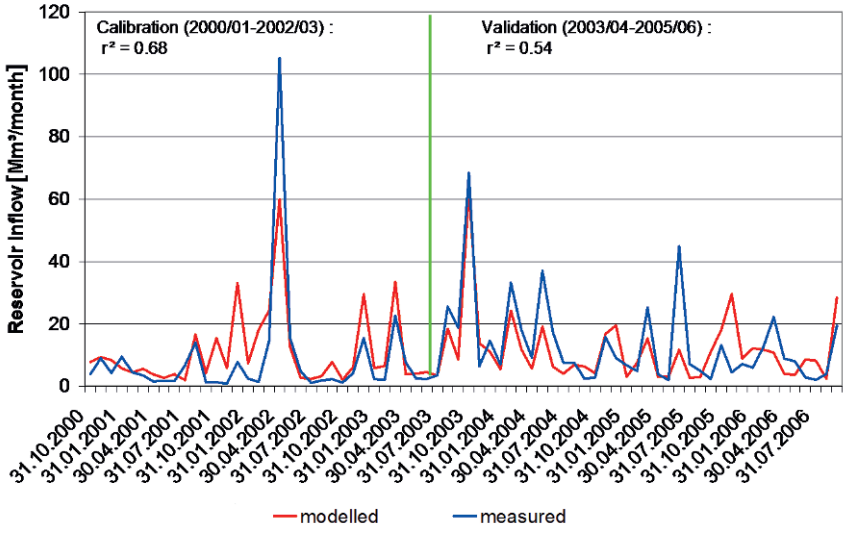

Fig. I-6.2.6: Measured and PRO-RES modelled monthly inflow into the Mansour Eddahbi Reservoir (Climate data base: measured data).

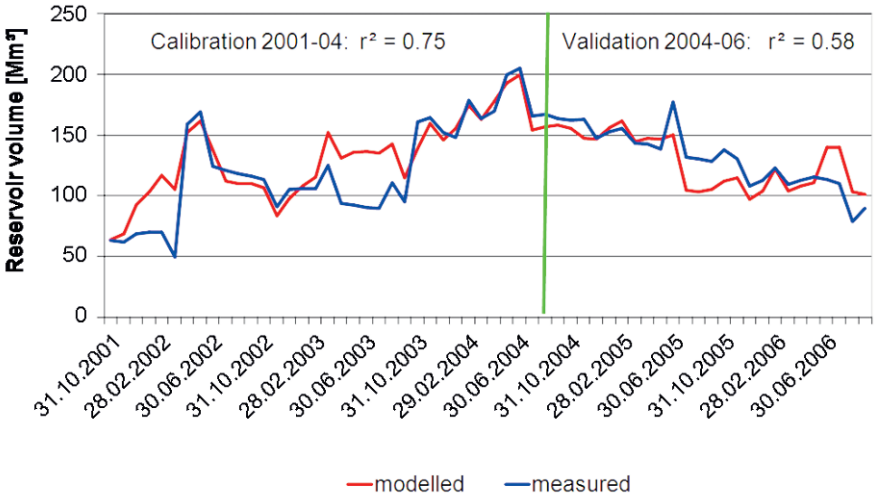

Fig. I-6.2.7: Measured and PRO-RES modelled monthly mean fill level of the Mansour Eddahbi Reservoir (Climate data base: measured data).

fill level. There are time series of calculations and pan measurements for local evaporation. In a simplified approach, water losses were taken as monthly constants and integrated as a lookup table into PRO-RES. These constants were slightly adjusted to match the measured filling level since evaporation estimations are not exact. The calibration and validation periods are shown in figure I-6.2.7.

In summarizing the preparation procedure for hydrological modeling with SRM and PRO-RES, it can be concluded that a monitoring tool has been built that is capable of a satisfactory simulation of snowmelt and rainfall runoff in the predominantly mountainous sub-basins of the Upper Drâa. Furthermore, very simple approaches of channel routing and water losses through irrigation, water releases from the reservoir and evaporation from its surface provide data of reservoir inflow and its fill level with a moderate quality.

Modeling results generally indicate that a precipitation event of at least 5 to 10 mm is needed to produce a measurable discharge or an increase of discharge in the Upper Drâa basin. Furthermore, only severe rainfalls are able to refill the reservoir. During the rest of the year, rain and snow-fed groundwater outflow assure basic water delivery to the reservoir, thereby ensuring its survival.

I-6.2.3 Hydrological analysis at different scales

Hydrological processes at the local scale

In arid and semi-arid landscapes, local scale soil hydrology is driven by scarce and irregular rainfall, high potential evapotranspiration, and soils that are characterized by coarse texture, high skeleton and low organic matter content. These soils are often shallow and their vegetation coverage low. Surface runoff is predominantly of the Hortonian type of infiltration excess, as the rainfall often shows high intensities. Infiltration in humid environments depends on initial soil moisture, but in arid and semi-arid landscapes, this factor is of minor importance.

Since rock fragments have a significant influence on hydraulic properties (e.g., Poesen and Lavee 1994; van Wesemael et al. 2000) the amount and texture of rock fragments affects the water storage capacity as well as the vertical water fluxes. These characteristics are modified by predominant geologic, climatic, and to-

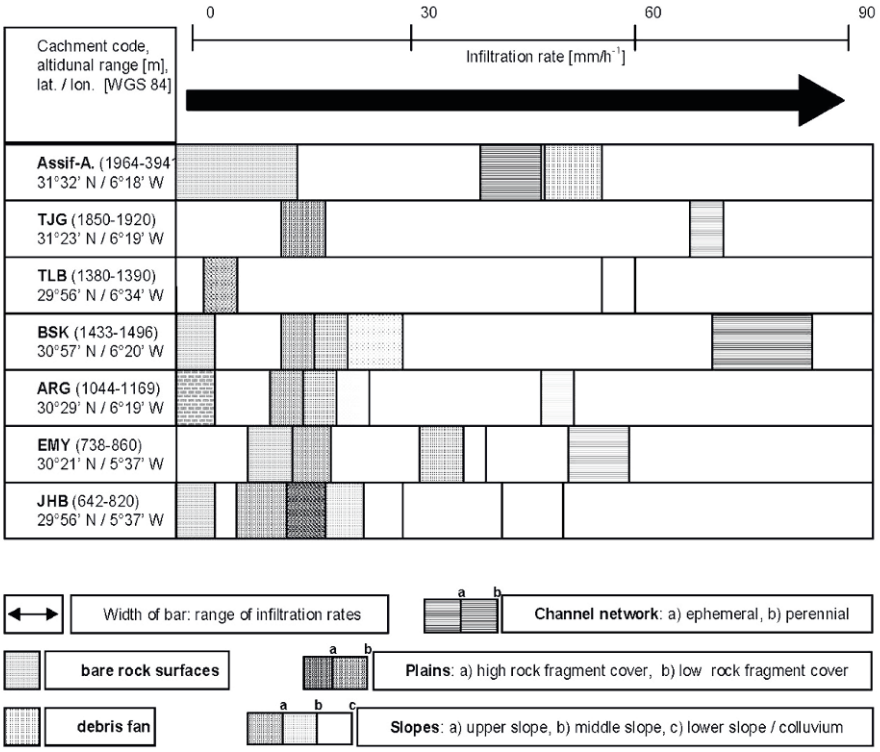

Fig. I-6.2.8: Infiltration rates of selected land units within the measurement transect (JHB=Jebel Brâhim, EMY= El Miyit, ARG=Arguioun, BSK= Bou Skour, TRL= Trab Labied, TJG= Taoujgalt, Assif-A.= Assif-n-Ait-Ahmed; for locations cf. chap I-4).

pographic properties as well as the type of vegetation cover. Ephemeral channel networks, such as wadis in the south and bedrock creeks in the mountainous regions, play an important role in the water regime. Channels with a high percentage of sand or coarse-grained material have a low water-holding capability, but high infiltration capacity. Terrain units with accumulations of fine-grained soil, such as colluvial pediments and topographic depressions, tend to store moisture. They therefore have the highest water contents with the lowest infiltration rates. A third typical regime comprises lithological units with shallow soils, low infiltration losses and lower moisture contents. This regime can be found on steep rock slopes and in topographic convexities. These three typical regimes can be found at all test sites in the Drâa catchment. A total of 23 terrain units were identified on the basis of measured infiltration behavior, dominant soil and hydrological properties in addition to topographic characteristics derived from high resolution DEMs. These units can be aggregated into categories based on their infiltration behavior, their predominant soil hydrological properties and their topographic characteristics (see fig. I-6.2.8).

Weber (2004) successfully applied a local scale hydrological model to a number of sub-basins in the Drâa catchment ranging in size from a few ha to some

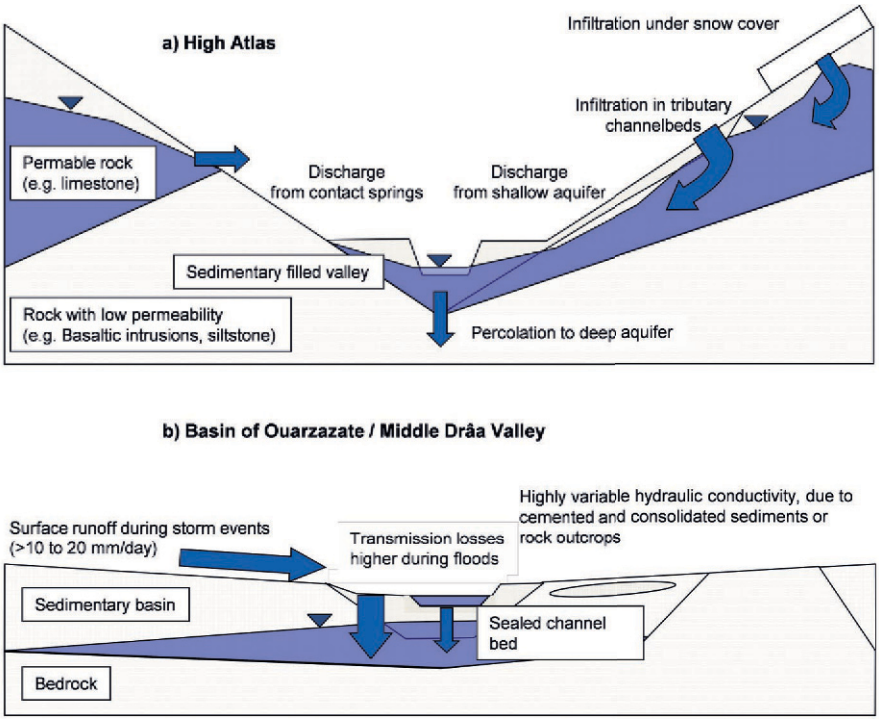

Fig. I-6.2.9: Discharge generating processes in the High Atlas Mountains (a) as well as the basin of Ouarzazate and the Middle Drâa valley (b).

km². He used near surface soil moisture data for model validation and, if available, discharge data. Although reasonable results were obtained at the local scale, upscaling to the regional scale failed. Therefore, a modified concept was developed for the regional scale (see fig. I-6.2.9). This is presented in detail below.

Quantification of hydrological processes at the regional scale

Figure I-6.2.10 shows the elevation dependency of annual rainfall within the Upper Drâa catchment for the period 2000-2008. Based on the digital elevation model SRTM (see sect. I-3.2), a mean annual precipitation of 203.7 mm can be calculated for the basin. Schulz (2006) measured the proportion of rainfall and snowfall at three altitudes (2,250, 3,260 and 3,850 m asl). A linear relationship can be established (r^2=0.99), as temperature decreases linearly with altitude. Knowing the amount of precipitation and the fraction of snow for a given altitude, a first impression of the precipitation within the catchment can be given (see fig. I-6.2.11). Fifty percent of the precipitation occurs in one-third of the total area situated above 1,900 m asl. Approximately 14% of the precipitation within the basin is snow.

For determining evapotranspiration losses and runoff-rates, discharge into the Mansour-Eddahbi reservoir was measured and compared with the precipitation. From 2000 to 2007 a mean annual discharge of 174 Mm³ was measured; this is equal to 11.6 mm (considering the catchment size of 14,981 km²). This leads to a runoff coefficient of 5.6%. Locally generated runoff is generally higher, as irrigation within the upstream oases decreases the stream flow measured in the reservoir considerably. Irrigation requirements within the catchment have been derived

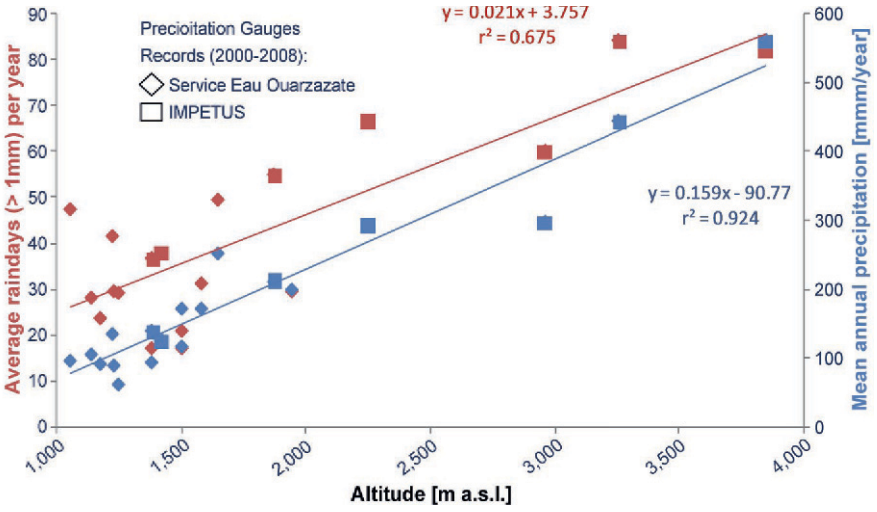

Fig. I-6.2.10: Elevation dependence of precipitation for the Upper Drâa catchment.

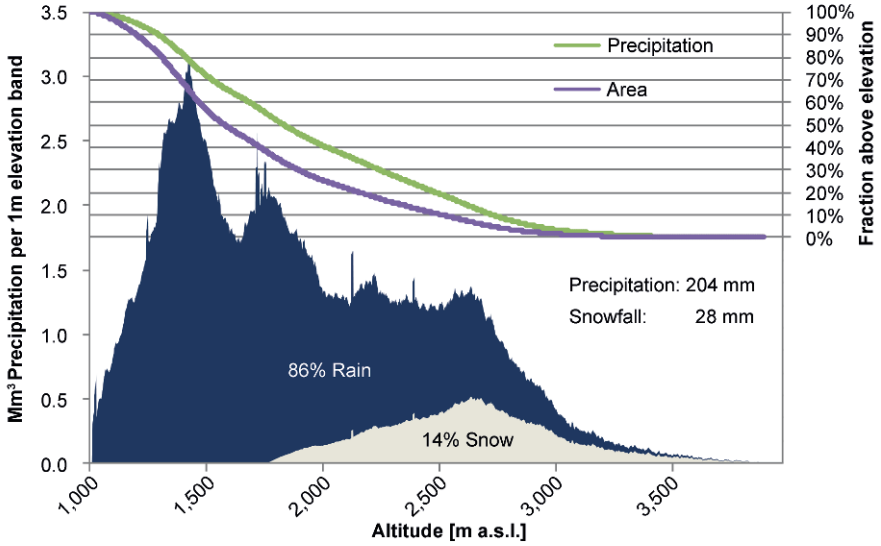

Fig. I-6.2.11: Mean annual precipitation and snowfall within the Upper Drâa catchment (2000-2007).

from official sources (Ministère des travaux publics 1998) for the year 1997/98. Brute irrigation requirements have been estimated at 95 Mm³ for the oases that rely predominantly on surface water for irrigation. Assuming an 18% evaporation loss (Ji et al. 2007), 116 Mm³ is used for irrigation. Adding this amount of water to the discharge measured at the reservoir, 290 Mm³ of total discharge can be assumed. This equals 19.3 mm, and it leads to a runoff coefficient of 9.5%.

Transmission losses are an important factor in the water balance of arid regions (El-Hames and Richards 1994). Losing streams prevail in the research area, but their net transmission losses vary according to discharge, stage height, flooded perimeter and clogging effects (Cappy 2006; Dunkerley 2008). Cappy (2006) used the MODFLOW model (Harbaugh et al. 2000), including the river package, designed to model the behavior of losing streams. Using this model, he estimated an annual riverbed infiltration of 48.2 Mm³, a return flow of 37.9 Mm³ and, therefore, an effective aquifer recharge of 10.3 Mm³ within the river segments between the Ifre, Ait-Mouted and Tinouar gauging stations. This river segment has a length of 92 km. Assuming an average width of 20 m, an effective infiltration rate of 3 mm/h results. As seen above, 21% of the infiltrated water recharges to the aquifer, whereas the rest is temporarily stored in the riverbank. The response time of different storage systems (aquifer, river bank/alluvial aquifer and snow) within the research area varies drastically. For the determination of recession coefficients assuming a linear storage, several techniques exist (Tallaksen 1995). Most of them rely on digital filtering of measured time series, which come to their limits when measurement uncertainty exceeds low flow. Griffiths and Clausen (1997)

noted the different behavior of subsystems. Aquifer systems are usually considered linear storage systems. Irrigation can be approximated as constant withdrawal, whereas snowmelt is dependent on climatic boundary conditions. In this study, base flow separation has been carried out manually for selected recession periods (see fig. I-6.2.12; validation: r^2=0.98). This assumed two aquifers, a bank storage within the alluvial deposits of the floodplain, and a lumped aquifer underlying the research area. During summer, snowmelt impacts are assumed to be negligible, but irrigation at least influences base flow recession. Furthermore, slower and low-yielding groundwater components might exist, but they cannot be analyzed due to noise in the low flow discharge data. This issue will be addressed in the section on uncertainty and in the discussion section. Due to the lack of knowledge about slow components, the estimated base flow recession of the lumped aquifer can be regarded as the upper limit. The base flow recession coefficient of 0.011 results in a 90% decrease in discharge after 209 days, whereas the bank storage recession of 0.113 results in a 90% decrease in discharge after 20 days. These findings go along with hydrogeological characterizations of karstic aquifers in Germany, leading to recession coefficients of 0.006 (ranging from 0.005-0.008; Schwarze 1999).

To conclude, two major aquifer systems dominate base flow within the Upper Drâa valley. The source areas of the perennial Dadès and M'Goun are karstified high mountain areas. Here, the groundwater recharges (to a large extent within the depth lines) and the base flow is generated with recession times long enough to sustain discharges in the basin throughout the summer. Alluvial aquifers buffer discharge peaks and sustain the basin's aquifer systems by increasing leakage rates. Local discharge in the basin is generated only during occasional severe rainfall events with more than 10 to 20 mm rainfall. These storm events occur infre-

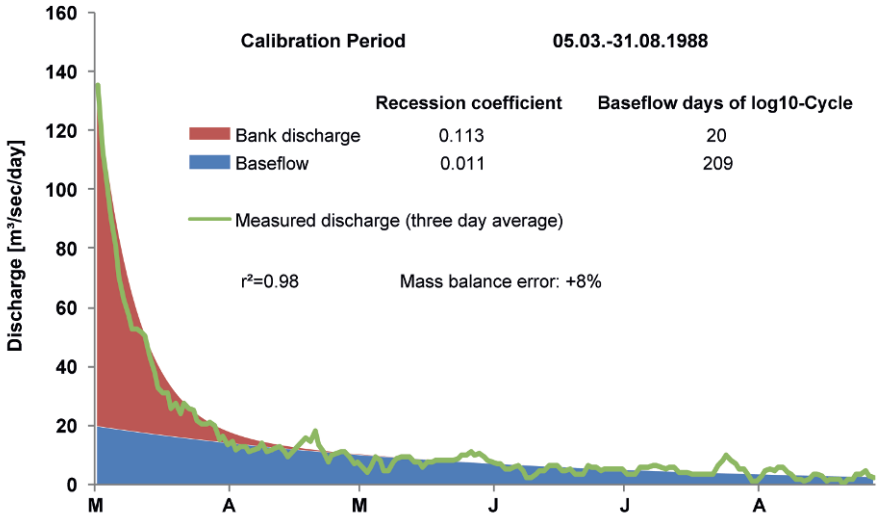

Fig. I-6.2.12: Baseflow recession analysis for the Upper Drâa catchment.

quently and are erratic, but they are essential for the operation of the downstream reservoir (Schulz et al. 2008). Figure I-6.2.9 gives a summarizing overview of the conceptual model developed for the Upper Drâa basin. This conceptual model is converted to a computational model as described in the following subsection.

Simulation of water fluxes: model development

For extrapolating quantifications of hydrological fluxes in the periods not covered by observations and for the spatial disaggregation of hydrological processes, it is essential to develop an appropriate hydrological model. In regions like the Drâa basin especially, where irrigation agriculture constitutes the dominant economy, there is a high demand for planning tools that consider Global Change effects. The following sections deal with the related model development, calibration, and validation.

A first approach to modeling the hydrologic behavior of the catchment is a simple rainfall-runoff relationship. A suitable polynomial regression can be found bet-

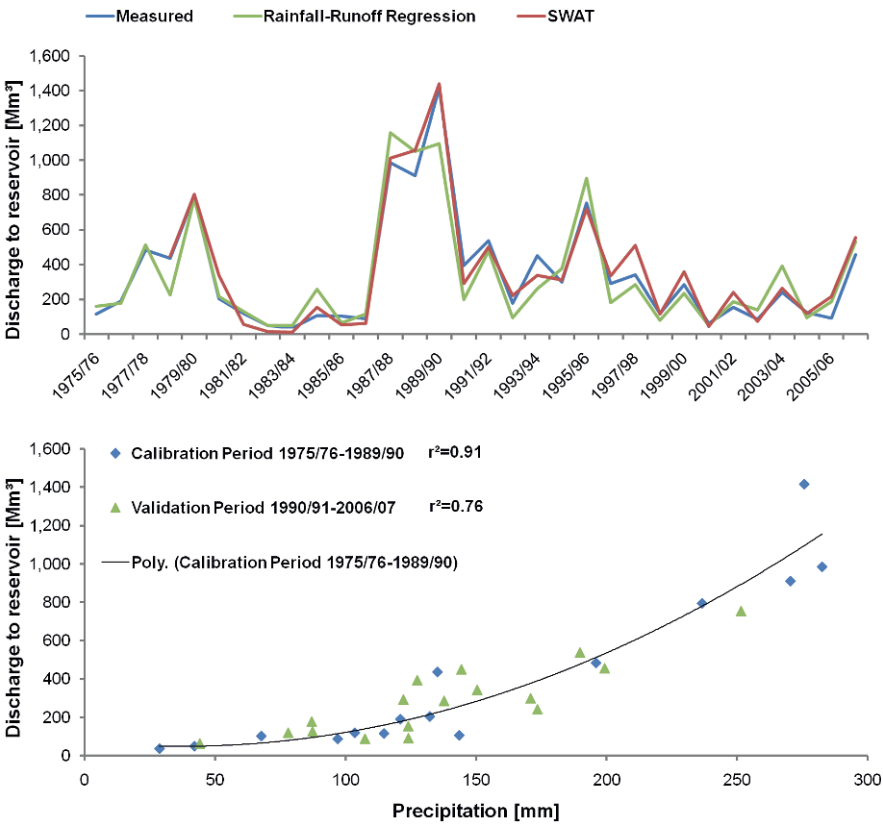

Fig. I-6.2.13: Annual rainfall-runoff relationship for the Upper Drâa catchment.

ween the mean annual precipitation of the 12 precipitation gauges within the catchment and the discharge into the reservoir (see fig. I-6.2.13). For the validation period, an r^2-value of 0.76 indicates an adequate quality of the relationship. Regarding monthly or seasonal variations of runoff, simple rainfall-runoff relationships come to their limits, as many processes delay or modify runoff. As pointed out in the previous section, these processes are at least the base flow, transmission losses, snow dynamics, and irrigation.

An adequate model, therefore, should at least be able to deal with these processes. As upscaling from local scale hydrological models fails in this complex region, the SWAT2005 model (Soil and Water Assessment Tool; Arnold et al. 1993) was chosen to quantify water fluxes in the Upper Drâa valley. SWAT2005 has proven to be capable of simulating hydrological processes in high mountain areas (Fontaine et al. 2002; Cao et al. 2006), as well as in semi-arid zones (Hernandez et al. 2000; Menking et al. 2003). SWAT has also been applied to small headwater catchments in the High Atlas (Chaponnière et al. 2008). SWAT2005 accounts for most of the relevant hydrological processes, including snow hydrology (Fontaine et al. 2002) and channel processes. At the same time, it maintains simple approaches (see fig. I-6.2.14) so that hydrologic complexity and data scarcity is considered at the same time.

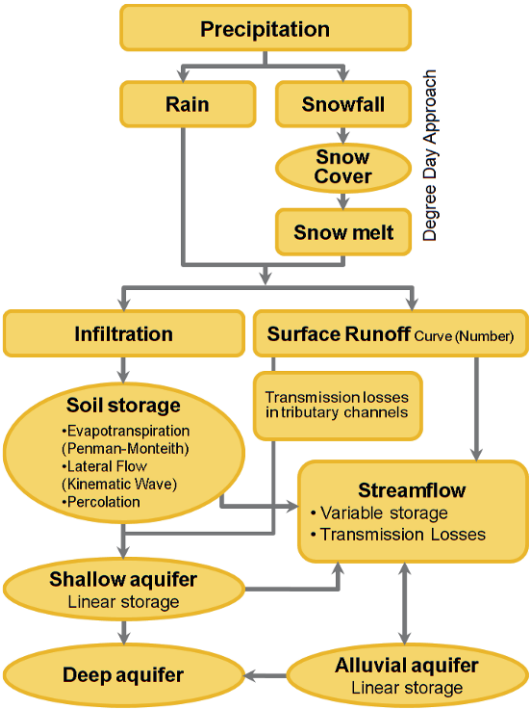

Fig. I-6.2.14: Water schematic diagram of the water movement as simulated by SWAT (Source: Modified after Arnold et al. 1993).

Water fluxes within SWAT are calculated on a daily basis for sub-basins. They consist of a number of hydrological response units (HRU), which are elementary spatial units which consider land use, soil type, and elevation. Within each HRU, precipitation occurs either as rain or snow, depending on temperature. Snowfall is added to the HRU's snow-pack, which starts melting when temperature rises. Snow-melt is quantified by a degree day approach (Fontaine et al. 2002). Snowmelt and precipitation either infiltrate or form surface runoff according to the NRCS Curve Number method (NRCS 1986). This is an empirical rainfall-runoff relationship that takes into account land cover and antece-dent soil moisture con-

ditions. Hence, infiltration is not directly modeled, but regarded as rain-fall minus surface runoff.

Infiltrating water is distributed between the different soil layers according to saturated conductivity and soil water content. If the hydraulic conductivity of the lower layer is lower than that of the upper layer, lateral subsurface flow (interflow) is calculated by a kinematic wave approach (Sloan and Moore 1984) that accounts for slope, slope length, and saturated conductivity.

Evapotranspiration is calculated using a modified Penman-Monteith approach (Allen et al. 1989), since required data are available and regional characteristics (aridity, frost, advective conditions) constrain the application of simpler approaches.

Water leaving the soil profile enters the shallow aquifer. Transfer through the vadose zone is simulated by a mean residence time. A fraction of the percolating water is diverted to a deep aquifer and permanently lost from the system. The shallow aquifer is represented by linear storages. Lateral flow and base flow enter the channel directly, whereas surface runoff is routed through tributary channels, accounting for transmission losses via effective conductivity (Lane 1983). These transmission losses enter the shallow aquifer directly. The remaining surface runoff enters the primary channel as well. Discharge is then routed using the variable storage concept (Williams 1969), again accounting for transmission losses.

Simplifying the original model concept, irrigation requirements are calculated on a monthly basis using CropWat (Allen et al. 1998). Since crop mix, extent of irrigated area, and irrigation sources vary considerably on an annual basis, the static crop model included within SWAT is not appropriate. These requirements are subtracted from available water at the respective channel nodes.

Extending the original model, elevation has been explicitly taken into account for the regionalization of the climate data, since precipitation dynamics vary considerably with elevation (see fig. I-6.2.10). The model therefore uses semi-generated precipitation series for altitudes not covered by precipitation gauges. Semi-generated time series consist of two components: measured precipitation from adjacent gauges adjusted for altitude and a stochastic component. Elevation dependency of daily precipitation has been analyzed using daily precipitation data from 23 gauges covering 8 years. Days on which at least 13 out of 23 gauges indicate rain have been considered wet. An increase of daily precipitation of 3.6 mm per km (r^2=0.68) has been derived (see eq. I-6.2.1).

$$PCP1_{day,HRU} = PCP_{day,Base} + 3.6 * \frac{mm}{km} * (elevation_{HRU} - elevation_{base}) \qquad \textbf{(eq. I-6.2.1)}$$

in which

$PCP1_{day,HRU}$ = Daily precipitation adjusted to HRU

$PCP_{day,Base}$ = Daily precipitation at gage (measured)

$elevation_{HRU}$ = Mean elevation of the HRU (km)

$elevation_{base}$ = Elevation of the gage (km)

In addition, random wet days need to be added, as the adjustment of measured precipitation is not sufficient to meet expected annual sums. Therefore, mean annual wet days and precipitation sums are estimated for a given HRU, and the deficits are determined. For each dry day in the time-series, a month-specific probability of additional rain occurrence can be calculated as given in equation I-6.2.2.

$$p_{rain} = \frac{PCP_{days,lack}}{days} \qquad \textbf{(eq. I-6.2.2)}$$

in which

p_{rain} = Probability of additional rain occurence

$PCP_{days,lack}$ = Estimated monthly number of wet days in HRU minus number of wet days at adjacent gage

$days$ = number of days in month

Precipitation amounts on these days can be calculated using a modified exponential distribution, as proposed by Neitsch et al. (1999; see eq. I-6.2.3)

$$PCP2_{day,HRU} = \frac{PCP_{lack}}{PCP_{days,lack}} * \left(-\ln\left(rnd_1\right)\right) \qquad \textbf{(eq. I-6.2.3)}$$

in which

$PCP2_{day,HRU}$ = Daily precipitation on randomly added day in HRU

PCP_{lack} = Estimated monthly precipitation in HRU minus adjusted precipitation from adjacent gage

$PCP_{days,lack}$ = Estimated monthly number of wet days in HRU minus number of wet days at adjacent gage

rnd_1 = Random number[0,1]

This procedure assures that within the basin, where most precipitation measurements take place, the generated time series matches the measurements, whereas in the high elevations, at least the characteristics of annual rainfall are represented satisfactorily.

Model setup

SWAT2005 has been set up using elevation data and soil and land use/cover data, as indicated in table I-6.2.1. Continuous soil data has been aggregated to 80 soil groups according to available water capacity, soil depth, and saturated hydraulic conductivity. These are generally the most sensitive soil parameters (A. Klose 2008). Based on Landsat imagery, two land cover types have been identified: bare

soil and steppe. In contrast, irrigated perimeters have been derived from the 1998 agricultural census (Ministère des travaux publics 1998). These areas (1.1% of the catchment area) are not further considered within SWAT2005, but they are considered within the subsequent CropWat simulation. Curve Number values have been set to default values for arid-rangeland (NRCS 1986). Groundwater and bank storage recession have been determined according to the base flow separation outlined previously. Effective infiltration rates of riverbeds have been set to 3 mm/h for main channels (see previous section). Precipitation data has been obtained from 12 gauges for 32 years, whereas all remaining climate data are simulated based on mean monthly data from shorter time series using the weather generator WXGEN (Richardson and Wright 1984). Mean monthly data required for

Table I-6.2.1: Data sources for the SWAT2005 simulation.

	Type	Resolution / Time Period	Processing	Source
DEM	Digital Elevation Model	90 m	-	SRTM
Soil	Soil Properties	-	211 soil profiles	A. Klose (2008)
	Soil Map	90 m	Multilinear regression CORPT-Approach	A. Klose (2008)
Landuse/-cover	Landsat	30 m	Determination of bare ground	
	Crop mix, irrigated Areas	1998	-	(Ministère des travaux publics 1998)
	CropWat parameters	-	-	(Allen, Pereira et al. 1989), (Ministère des travaux publics 1998)
Climate	Precipitation	daily, 12 stations 1975-2007	gap filling elevation adjustment	Service Eau Ouarzazate
	Temperature Solar radiation Wind speed Relative humidity	daily 7 stations 2001-2007	gap filling	IMPETUS
Discharge	Reservoir level	monthly 1972-2007 daily 1983-2007	Correction of sedimentation effects	Service Eau Ouarzazate

the weather generator has been obtained from the IMPETUS climate station network (see sect. I-4.2).

The SWAT2005 model was calibrated and validated against the level of the Mansour-Eddahbi reservoir. The model results were evaluated after a 2-year warm-up period. During calibration, the curve number was increased by 4.5 points, and the available water capacity was increased by 3%. Furthermore, the fraction of deep groundwater recharge was set to 15% of the percolating water. First model runs with a base flow recession coefficient of 0.011, as estimated from the discharge data (see previous section), resulted in too little base flow during summer. Therefore, the base flow recession was calibrated as well. A base flow recession of 0.0037 matched the observed data best. The effective infiltration rate of tributaries was set to 10 mm/h.

Goodness-of-fit tests were carried out, and they indicated a good representation of measured discharge (r^2=0.91, modeling efficiency=0.91, index of agreement=0.98; fig. I-6.2.15).

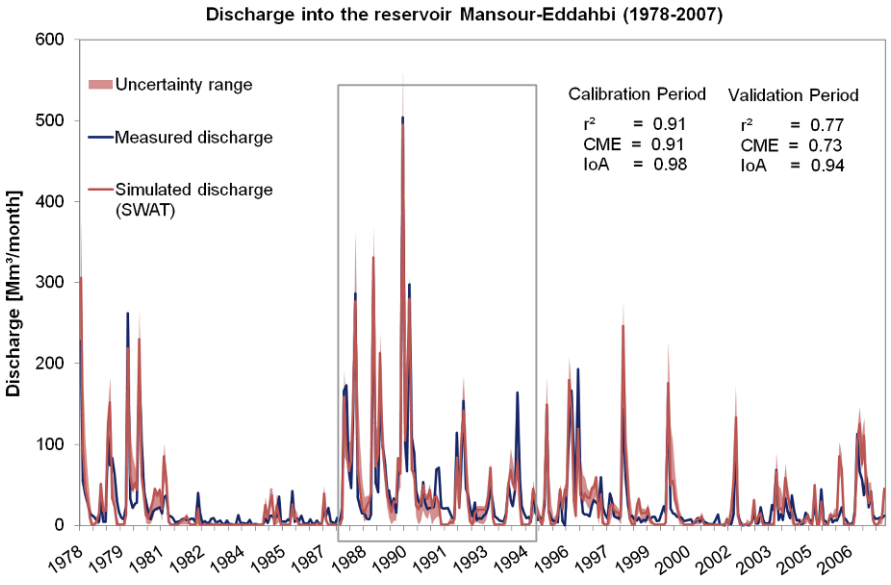

Fig. I-6.2.15: Monthly stream flow at of the Upper Drâa measured at Mansour-Eddahbi Reservoir (14,981 km²).

Model validation

During the validation period, the model quality was still acceptable (r^2=0.77, model efficiency=0.73, index of agreement=0.94; see fig. I-6.2.15). However, discharge is only one way of judging the applicability of a model. For estimating

evaporation losses from the reservoir and ongoing sedimentation that is infrequently monitored by bathymetric surveys, additional validation parameters are desirable. Schulz (2006) performed a snow cover monitoring for the High Atlas using the normalized difference snow index (Salomonson and Appel 2004), which was also suitable for model validation. Figure I-6.2.16 shows the comparison of measured and simulated snow covers for the period 2001-2006. Though absolute coverage differs, the dynamic and temporal extents of measured and simulated snow cover are similar in the elevation zones considered (2,000-2,500 m asl and 2,500-3,000 m asl). Furthermore, the model calculates 12.2% of precipitation as snow, which is in good accordance with the 14% obtained from field measurements (see fig. I-6.2.11). Overestimations of absolute cover may derive from the simple degree-day-approach, which does not account for slope, exposition, wind deposition and other factors.

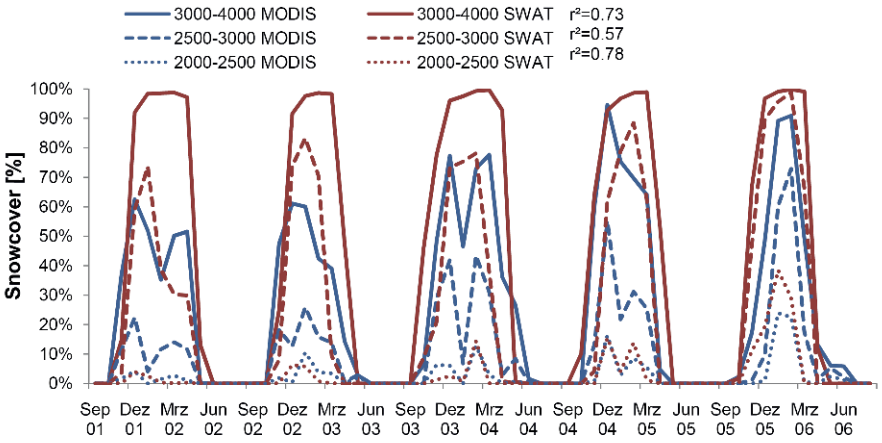

Fig. I-6.2.16: Snow dynamics in the higher elevations of the Upper Drâa catchment 2001-2006. Measured: NDSI; Simulated: SWAT2005.

The irrigation amount estimated by contrasting water availability calculated by SWAT with the irrigation requirements estimated by CropWat can hardly be validated. The calculated irrigation requirement equals 1,445 mm/year (236 Mm³ for 16,300 ha irrigated surfaces), of which, 1,032 mm/year (165 Mm³) can be satisfied by applying surface water. The local agricultural authority ORMVAO (*Office Régionale de Mise en Valeur Agricole de Ouarzazate*) estimates irrigation requirements of 213 Mm³, of which, 139 Mm³ can be satisfied by using surface water (Ministère des travaux publics 1998).

Model results

Having validated the model, flow characteristics that have not been covered by measured data can be analyzed. Runoff coefficients show high variability, ranging from 4% in 83/84 (a very dry year) to 30% in 89/90 (a very wet year), with a mean of 19%. Mean annual precipitation and discharge patterns are given in figure I-6.2.17. The highest precipitation occurs in October, whereas the highest discharge occurs in March. The model generally overestimates discharge in winter, whereas it underestimates discharge in summer. Table I-6.2.2 provides the mean annual water balance for the years 1978-2007. The dominant part of the water balance is evaporation (79.3%). The surface runoff (9.3%) and base flow (9.2%) components of runoff are almost equal, whereas interflow can be considered negligible (0.5%). The groundwater recharge is 3.7%, of which, 1.6% is direct recharge and 2.1% is indirect recharge, occurring in the wadi beds. Irrigation requirements can be satisfied up to 69% using surface water (5.2% of precipitation).

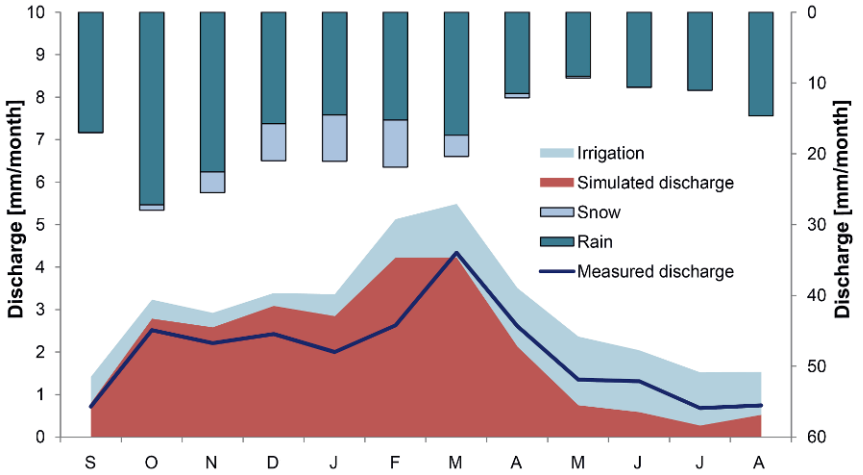

Fig. I-6.2.17: Comparison of mean annual observed and simulated discharge at the Mansour Eddahbi Reservoir (14,981 km²).

An uncertainty analysis was carried out to account for parameter uncertainty within the model. The following parameters and ranges have been used:

- Curve Number (±10 points),
- available soil water capacity (±30%, see A. Klose 2008),
- fraction of percolating water that enters the deep aquifer (10-20%),
- base flow recession coefficient (0.001-0.015),
- effective conductivity of tributary channel beds (5-20 mm/h).

Table I-6.2.2: Water balance of the Upper Drâa catchment (14,981 km²) 1978-2007, modeled with SWAT2005.

Water balance Upper Drâa 1978-2007	mm	Fraction of Rainfall
Precipitation	212.5	100.0%
Snow	26.0	12.2%
Rain	186.5	87.8%
- Evapotranspiration	168.6	79.3%
- Direct GW recharge	3.5	1.6%
= Runoff	40.4	19.0%
Surface	19.8	9.3%
Interflow	1.1	0.5%
Baseflow	19.5	9.2%
- Indirect GW recharge	4.5	2.1%
= Channel Discharge	35.9	16.9%
- Irrigation	11.1	5.2%
= Reservoir inflow	24.9	11.7%

Using Latin-Hypercube sampling, 100 simulations were carried out. The median of these model results is bracketed by 34% quantiles, according to the ±1 standard deviation of the normal distribution. The remaining simulations were dropped, as they represent unrealistic parameter combinations. Within this range, 75% of the measured data can be found (assuming 10% measurement uncertainty (Abbaspour et al. 2004; Harmel et al. 2006)). The uncertainty range is given in figure I-6.2.15 (light red band). Robust linear relationships of uncertainty ranges and total discharge can be established for this surrounding. The monthly discharge uncertainty was 51% (r^2=0.75), and the annual discharge uncertainty was 41% (r^2=0.67).

Discussion

SWAT obviously outperforms the regression model developed earlier (see fig. I-6.2.13). The explicit modeling of storage systems (soils and aquifers) and the favoring of different runoff mechanisms due to changing daily precipitation intensities can be observed in 1987/88 and 1989/90, albeit, similar annual precipitation sums are used, and the simulated runoff varies by 431 Mm³ (28.7 mm). After a prolonged drought period in 1987, exhausted stores were recharged prior to runoff, whereas in 1989, a higher fraction of rainfall contributed to runoff, favored by high daily precipitation intensities and already-filled aquifers. This behavior can only be reproduced by a model that explicitly accounts for storages and processes. The same buffering influences can be noted for the inner-annual variations of runoff. The highest precipitation amounts can be observed in October, when soil water content and depleted aquifers refill along with a buildup of snow cover. The

highest discharge occurs in March due to intensive precipitation, due to the depletion of snow stores and a faster groundwater reaction.

The model concept has been adapted to suit local conditions, though discrepancies in observed and simulated discharge can be observed. During summer, observed discharge is underestimated by the model. This can either be a result of underestimating base flow during the dry season or overestimating irrigation requirements.

Further enhancements of SWAT could include a second linear storage aquifer and a dynamic component in CropWat, adapting irrigated surfaces to water availability. Both adaptations seem reasonable since slow base flow components as well as limitations of the irrigated surface can be observed during prolonged droughts. In both cases, the data required is difficult to obtain. These model concept uncertainties cannot be quantified and, therefore, rather represent an outlook on further tasks.

Regarding the complex setting of the watershed, the magnitude of parameter uncertainty appears reasonable and can be used for further assessments of scenario uncertainty.

I-6.2.4 Sub-surface flow in the Middle Drâa basin

Recurrent droughts, unplanned groundwater extractions, and increasing groundwater salinity deteriorate the water resources of the Middle Drâa valley. Soil salinity (see subsect. I-6.2.5), population growth, and urbanization (see subsect. I-8.1.2) worsen the situation even more. Due to the fact that the climate is hyper-arid, husbandry must rely on irrigation by surface water from the upstream Mansour Eddahbi reservoir and on individually pumped groundwater. Agricultural production, which consumes the most water, concentrates on the six Drâa oases: Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua, and M'hamid (see fig. I-3.2.3). In addition, groundwater is pumped mainly in agricultural areas along the tributaries of the *Oued* Drâa and locally within sedimentary basins adjacent to the *Oued* Drâa (see fig. I-3.2.3; see subsect. I-8.2.2).

The groundwater system of the Middle Drâa valley depends strongly on the hydrological regime due to the stream flow - aquifer interaction. The length of the *Oued* Drâa from the Mansour Eddahbi reservoir is more than 200 km down to Lake Iriki in the Saharan foreland (see fig. I-3.2.3). Because the stream flow of the *Oued* Drâa has been regulated since 1972, water is released periodically from the Mansour Eddahbi reservoir several times a year, depending on the filling level. Stream flow can be retained in five minor reservoirs along the *Oued* Drâa for irrigation distribution (ORMVAO 1995; Ouhajou 1996; Doukkali 2005; Martin 2006). Regarding the time period of 1973/74 to 2005/06, the mean volume of annual discharge amounts to 211 Mm^3 (data from ORMVAO). In dry periods, it can decrease far below 100 Mm^3, whereas in very humid periods, it can reach more than 600 Mm^3. Before 1972, the *Oued* Drâa drained as an ephemeral river into Lake Iriki. The mean annual river discharge was 416 Mm^3 (1937/38 – 1963/64),

measured at the entry of the Middle Drâa valley (the reservoir outlet today). From discontinuous data measured at Zagora, a theoretic mean annual discharge of about 205 Mm³ is derived (based on data of 1940/41-1950/51 and 1962/63-1963/64 from Chamayou 1966).

To cover irrigation and drinking water demand, groundwater has been increasingly pumped from the alluvial aquifers along the Drâa and its tributaries over the last decades. Even the subjacent fractured rocks are tapped. Groundwater studies in the Middle Drâa basin have been conducted since the early 20th century, as documented by Margat (1958), and have been composited in numerous reports (e.g., Compagnie Africaine Géophysique 1947; Margat 1958; DRE 1976; ORMVAO 1995; Aoubouazza and El Meknassi 1996; DRH 2001).

In this study, groundwater dynamics and hydrogeochemical processes in the Middle Drâa basin were investigated to identify geogenic phenomena and anthropogenic influences. Therefore, the groundwater budget for the aquifers along the Middle Drâa valley was modeled to support regional groundwater management (Heidecke et al. 2008; S. Klose et al. 2008). A conceptual groundwater balance model (BIL) was developed for the Middle Drâa valley. Geological and hydrogeological evaluations are based on field campaigns and existing data. (Ground-) water and rock sampling provides an actual data base for hydrogeochemical analysis. Exemplary test sites (around Oueld Yaoub and Fezouata) were selected at the sub-regional scale in order to upscale the findings to the regional aquifer systems in the Middle Drâa valley. In total, 95 water samples were taken from 67 stations between 2005 (spring and autumn) and 2007 (spring). Additionally, 26 rock samples were taken at 22 outcrops in the Middle Drâa basin.

Aquifer setting

The Middle Drâa basin extends on the southern flank of the central Antiatlas over an area of approximately 15,000 km². The underground is made up of metamorphic sedimentary-volcanoclastic successions covered by a series of sedimentary rocks (see sect. I-3.1). The sedimentary rocks are folded and dipping generally southwards (Destombes 1985; Helg et al. 2004). The Antiatlas represents an Appalachian-style landscape sloping southwards. Ridges and cuestas of resistant arenites (e.g., the Jbel Bani) alternate to valleys and sedimentary basins, where less resistant schists occur (Riser 1988). The southward opening Drâa valley forms gorges, where the river cuts through the ridges and cuestas that act as natural hydraulic barriers. The altitude ranges from around 2,500 m asl in the Central Antiatlas to 421 m asl at Lake Iriki (see sect. I-3.2). The heterogeneity of the occurring rocks and the structural setting is decisive for the complex hydrostratigraphy, the aquifer structure and, therefore, the water fluxes and water availability.

The Middle Drâa basin is covered by 53% fractured, 42% porous media and 5% fractured and partly karstic rocks according to the geological map of Morocco 1/500,000 (Ministry of Economy 1959). The *Oued* Drâa represents the only hy-

draulic connection to the basin's upper catchment. According to the general southward dipping of strata at the southern slope of the Antiatlas Mountains, the northern limit of the aquifer catchment is roughly the same as the hydrological catchment. The most productive aquifers are located along the deeply incised Drâa, one beneath each of the six palm groves ('oasis aquifers'). The oasis aquifers form an aquifer-cascade that is subdivided by natural hydrogeological barriers. Quartzites, sandstones and siltstones, as well as tectonic lineaments, border and separate each oasis aquifer. These porous alluvial aquifers overlay fractured Ordovician schists which act as aquitards. The schists reveal a highly weathered fringe of varying thickness on top. This weathered zone is assumed to be part of the shallow aquifers due to the degree of fracturing and disaggregation. The alluvial deposits along the Drâa and in the Feijas can form multilayered aquifers of generally high, but locally highly variable permeability. The properties of the oasis aquifers have been locally tested (see table I-6.2.3; Chamayou 1966, Office Nationale des Irrigations 1973; Aoubouazza and El Meknassi 1996; DRH 2001). Accordingly, the hydraulic conductivities of the oasis aquifers range between 3 10^{-4} and 7 10^{-3} m/s, depending on the local facies. The Palaeozoic successions of alternating schists, quartzarenites, and sandstones form a complex system of aquitards, revealing low permeabilities which are dependent on the grade of fracturing (Chamayou et al. 1977; Ismat 2008). Limestones and dolomites of Devonian and Early Cambrian age are partially karstified. Thus, they represent aquifers with moderate and highly variable hydraulic conductivity. Precambrian magmatic and metamorphic rocks of the basement act also as aquitards or even as aquicludes.

Table I-6.2.3: Properties of the oasis aquifers along the *Oued* Drâa: mean hydraulic conductivity *K*, aquifer thickness *M* and aquifer surface (after Chamayou 1966).

Aquifer	K [m/s]	M [m]	Aquifer surface [km²]
Mezguita	$1.0*10^{-3}$	25	45.0
Tinzouline	$6.8*10^{-3}$	25	69.0
Ternata	$3.0*10^{-3}$	25	45.4
Fezouata	$1.5*10^{-3}$	30	72.1
Ktaoua	$2.5*10^{-4}$	40	50.0
M'Hamid	$2.7*10^{-4}$	50	124.6

Regional groundwater dynamics

The subsurface water flow within the aquifers along the chain of the oasis is the dominant lateral flux (Chamayou 1966; DRE 1976; Chamayou et al. 1977; DRH 2001). Regional groundwater discharge from one oasis aquifer to another is limited by the hydraulic barriers at the downstream end of every oasis aquifer. The oasis aquifers are recharged by infiltrating river water and by lateral inflow from the circumjacent system of aquitards along with the adjacent sedimentary basins. Direct groundwater recharge to the oasis aquifer is negligible (Weber 2004). Natural recharge within the Middle Drâa basin feeds the lateral afflux from the aquitard system toward the oasis aquifers. Lateral afflux occurs as local preferential flow from the adjacent fractured aquitards and as subsurface flow from tributary *Oueds*. Groundwater in the adjacent sedimentary basins forms an interconnected reservoir discharging into the oasis aquifers. Groundwater extractions that are mainly for irrigation purposes lead to a local drawdown of the water tables. Decreasing availability of surface water results in an enhanced depletion of groundwater levels (DRH 2001).

Concept of the regional aquifer system

The distribution of the inorganic groundwater composition verifies the existence of three main aquifer systems within the basin. Groundwater of almost natural background composition occurs in the extensively used parts of the aquitard system (Ca-HCO_3 - type). Groundwater of heterogeneous composition reflects various hydrogeochemical processes in the aquifers of the sedimentary basins adjacent to the Drâa (Mg-HCO_3 to Na-SO_4 – type). A quite homogenous group of strongly saline water is found within the oasis aquifers (Na-Cl and Na-SO_4 – type). Moreover, the surface water of the Drâa (coming from the upstream reservoir) is relatively less saline (Ca- SO_4 – type). Further hydro-geochemical methods are approached in order to overcome the lack of hydraulic data and to support the quantification of the groundwater balance. Thus, the distribution of groundwater types and the groundwater evolution is depicted along the Drâa and along the main pathways of lateral affluxes.

Along the oasis, aquifers recharge discontinuously after stream flow and continuously as afflux from the adjacent aquitard system. Furthermore, the infiltration and return flow of irrigation water increases groundwater recharge. Hydro-chemical and isotopic evaluations are proof of groundwater salinization by the reflux of irrigation water, which is influenced by evaporation. Spatially irregular increases in, for example, sulfate concentration point to enhanced leaching of gypsum and anhydrite, both intensified by irrigation. In contrast, infiltrating river water dilutes groundwater in the oasis aquifers. This net recharge is also proven by piezometric data, which are automatically recorded at three piezometers of the ORMVAO. The afflux from the aquitard system also dilutes the groundwater in the oasis aqui-

fers, but to a smaller degree, as mixing calculations show. The aquitard system is fed by regional recharge, which depends mostly on climatic conditions and topography (Sanford 2002). Recharge rates are estimated using the chloride mass balance approach (CMB) and are regionalized following a simple lithofacies concept. Recharge rates account for 2.30% of the mean annual precipitation for the fractured rocks of the aquitard system and 3.17% for the porous sedimentary deposits, respectively, along the *Oueds*. A possible source of error is the limited data on rainfall chemistry and recharge times, as groundwater ages can be more than 50 years following local Tritium analyses (Cappy 2006).

Regional groundwater discharge takes place to and from the oasis aquifers and by groundwater exploitation. If surface water is available, the amount of groundwater pumping is reduced. Furthermore, groundwater can evaporate over relatively small areas upstream of the hydraulic barriers between the oasis aquifers. At these places, the groundwater table can rise above the critical depth of capillary rise due to backwater in front of the barriers. Transpiration losses directly from the groundwater reservoir occur only by deep-rooting plants, such as Acacia trees. Significant losses occur due to evapotranspiration caused by irrigation agriculture. The drinking water supply amounts to only a small fraction of the total groundwater extraction. Therefore, it plays a minor role at the regional scale, but it is an important part of the local water balance. Percolation to deep aquifers is widely unknown and is assumed to be negligible for this study. Upwelling from deep aquifers, probably along faults, is locally suggested by aerated water (Cappy 2006)

Groundwater balance assessment

The groundwater balance model BIL was developed for the assessment of groundwater availability at the basin scale in the Middle Drâa valley. BIL estimates the groundwater budget for each of the oasis aquifers. Temporal resolution is annually due to the limited availability of data. The model approach considers the hydraulic connection of the oasis aquifers using a linear storage-cascade. BIL is thus capable of projecting scenarios for the whole chain of oases.

Model concept and parameterization

The input data of the aquifer budgets are based on our own hydrogeological studies and data provided by the Moroccan partners (DRPE, Service Eau, ABH Souss-Massa-Drâa, and ORMVAO) and literature. All recharge and discharge components of the groundwater balance are summarized in equation I-6.2.4.

Recharge at the basin scale (R_t) is assessed using linear storage units. Recharge within the Middle Drâa basin is therefore estimated by applying recharge coefficients gained from the chloride mass balance method (see above) for the subcatchments of each oasis according to different lithofacies. Precipitation data is

$$V_{gw} = V_{prior} + R_r + R_l + R_i + R_p - Q_i - Q_s + F_{gw} - D_{gw} \quad \textbf{(eq. I-6.2.4)}$$

Vgw	=	Volume of available groundwater
V_{prior}	=	Volume of available groundwater of the prior year
R_r	=	Regional recharge
R_l	=	Recharge by river bed infiltration
R_i	=	Recharge by infiltration of irrigation water
R_p	=	Return flow of pumped groundwater for irrigation
Q_i	=	Amount of pumped irrigation water
Q_s	=	Amount of pumped groundwater for water supply
F_{gw}	=	Groundwater afflux from the upstream aquifer
D_{gw}	=	Groundwater discharge to the downstream aquifer

provided by the *Service Eau Ouarzazate* from the Zagora station for the period 1973/74 to 2004/05.

As riverbed infiltration (R_l) cannot be precisely determined, and as evapotranspiration losses are unmeasured, the losses along the stream flow of the *Oued* Drâa are assumed to range between 10 and 20% (Chamayou 1966; ORMVAO 1995).

The spatial distribution of irrigation water demand in the oases is derived from data from the ORMVAO. The infiltration of irrigation water derived from the *Oued* Drâa (R_i) and the return flow of pumped groundwater (R_p) is approximately 8% (ORMVAO 1995).

Groundwater is pumped to cover irrigation demand (Q_i), which is not met by available surface water from the Drâa. The irrigation demand is assumed to be the crop water demand for optimal growth under consideration of irrigation efficiency (flood irrigation efficiency: ~ 50%; Bos and Nugteren 1990). Crop water demand is assessed based on the calculation of evapotranspiration, using the Penman-Monteith approach (Allen et al. 1998). Groundwater withdrawal for water supply (Q_w) is calculated based on demographic data.

The groundwater discharge from one oasis aquifer to another and the afflux, respectively, is realized by the calculation of 1D groundwater flow (F_{gw}, D_{gw}) based on the Darcy Equation.

Model results

The results of the groundwater balance modeling for the period 1973/74 – 2005/06 are presented in figure I-6.2.18. The dynamic of the filling levels of the oasis aquifers show that the most significant fluctuations are due to recharge by infiltrating river water and extractions for irrigation purposes (see fig. I-6.2.19). The mean

basin-wide groundwater recharge amounts to 1% of the available groundwater volume (e.g., at Mezguita). In contrast, the mean recharge by riverbed infiltration accounts for 11% of the available groundwater volume. The recharge by infiltrating irrigation water from the *Oued* Drâa and by return flow from pumped groundwater is estimated to be 2.4% of the available groundwater volume. For all oases, the mean filling level of aquifers is 59%. In drought periods, it decreases to 45%, whereas in humid periods, it amounts to 73%. The buffer function of the groundwater reservoir is, therefore, obvious. Assuming no recharge, the groundwater reservoirs of the Middle Drâa valley would last another six to nine years before becoming completely dry.

Accurate calibration and validation of the model results are not possible due to the limited resolution of the hydrodynamic data. Plausibility checks against observed

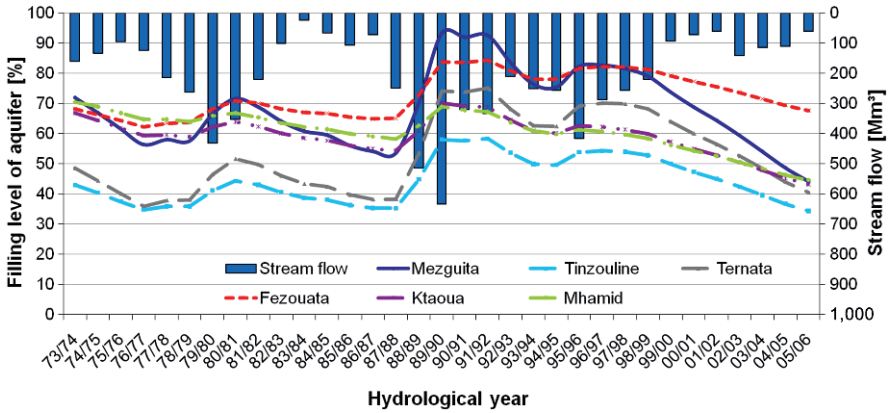

Fig. I-6.2.18: Results of the groundwater balance modelling with BIL for the period 1974 – 2006 – filling levels of oasis aquifers and the volume of stream flow.

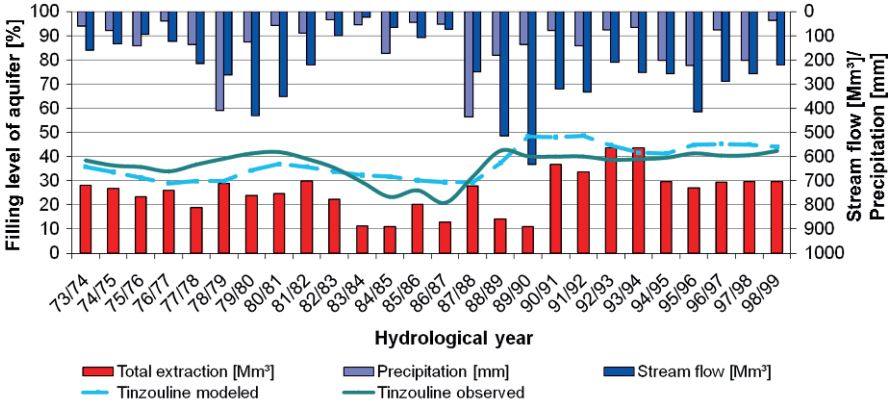

Fig. I-6.2.19: Plausibility check of the groundwater balance modelling with BIL at the oasis aquifer Tinzouline.

piezometric data reveal a satisfying accordance with the model (see fig. I-6.2.19; data from DRPE). The root mean square error reaches 10% in comparison to the groundwater level data at the supporting points. The modeled filling levels of the aquifers reveal a damped reaction to high rainfall and high extraction amounts, as an example from the Tinzouline oasis shows (see fig. I-6.2.19). The effects of a smooth development of modeled filling levels is expected to be stronger within a seasonal cycle that considers extreme rainfall events. Therefore, an annual resolution of calculations limits the support of water use strategies in agriculture, which focus on seasons. But BIL provides an estimation of long-term impacts on groundwater resources, such as the influences of climatic change (see chap. II-3 and sect. II-5.2). The model is designed to estimate the available groundwater resources on the regional scale, not on the local scale. It thus represents a tool for regional aquifer planning and management.

According to the sensitivity of recharge by infiltrating river water and extractions for irrigation purposes, enhanced water management appears to be worthwhile. Consequently, comprehensive investigations on water extraction and water distribution are required in addition to the urgent need for groundwater observations and the determination of geohydraulic parameters (ORMVAO 1995).

I-6.2.5 Soil salinity: Measurements, processes, and simulations

Soil salinization is a threat to irrigation agriculture mainly in the oases of the Middle Drâa valley. Soil salinization also occurs outside the oases and in the Upper Drâa basin, but is mainly a geogeneous process that depends on the dissolution of salts from the underlying rocks. A gradient of salinity in surface water, groundwater, and soil from north to south in the Middle Drâa valley can be clearly depicted (see fig. I-6.2.20, for oasis location see fig. I-3.2.3). An increase in salinity can be related to different processes, but in the case of surface water, it depends mainly on evaporation. Evaporation losses generally rise with travel time along the flow path, and evaporation rates increase toward the south due to increasing aridity. This can also be observed in groundwater and soil salinity, as a close feedback between groundwater and soil salinity exists. Water from the aquifers is pumped to the fields for flood irrigation, where the water evapotranspirates and salts are left behind. These salts partially accumulate in the soils and are partially washed out to the aquifers again. Further downstream, this salt-enriched water is again pumped and used for irrigation. The salt concentration of the groundwater thus increases more and more along the main flow direction from north to south. This process is further aggravated by higher potential evapotranspiration rates in the southern part of the Middle Drâa valley. Therefore, there is a relationship between climate, irrigation water quality, and soil salinity on the regional scale.

Two local scale studies have been conducted in the focus areas of Feija de Zagora and the village of Ouled Yaoub (fig. I-3.2.3). In the first study, soils irrigated

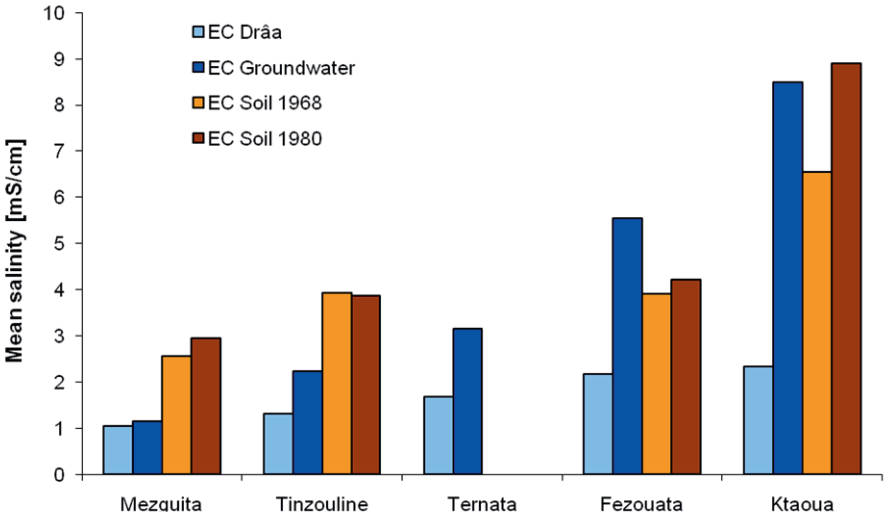

Fig. I-6.2.20: Mean salinity of surface water, groundwater and soil within the Drâa oases (left: northern oases, right southern oases, see fig. I-3.2.3. Source: Bouidida 1990, soil salinity in saturation paste, data for Ternata is lacking).

with groundwater of different quality have been examined in order to analyze the relationship between irrigation water and soil quality. Gardens in the study area are irrigated exclusively with groundwater, and the usage history is never longer than 30 years. The second study aims to map and to explain the spatial patterns of salts within the gardens of the Ouled Yaoub village belonging to the Tinzouline oasis. Irrigation agriculture has been applied for centuries here, and both groundwater and surface water are used for irrigation.

In both studies, a simple relationship between the quality of irrigation water and soil quality could not be established, and other factors appeared to influence

Table I-6.2.4: Characteristics of investigated soil profiles and irrigation water wells in the *Feija de Zagora* (EC = electric conductivity; data source: IMPETUS field campaign autumn 2005).

Observation point	Groundwater EC[mS/cm]	Soil EC [mS/cm]	Sand [%]	Silt [%]	Clay [%]	Garden age [years]
1	0.8	11.6	48	32	20	6
2	1.2	20.5	58	21	21	3
3	1.1	13.0	70	17	13	10
4	0.8	5.6	78	13	9	18
5	1.8	17.9	57	18	25	12
6	0.8	29.5	75	13	12	30

soil salinity. In the Feija de Zagora case study, soil salinity could be explained by irrigation water quality up to 50% (r^2=0.52). Furthermore, soil salinity seems to depend on soil texture and garden age (table I-6.2.4).

In the case of Ouled Yaoub, the situation is even more complicated. No clear explanation for the spatial pattern of salts was found as the influences of cultivated crop type, irrigation water quality and quantity, irrigation with surface water, soil properties, and groundwater flow systems superpose. The salinity of the groundwater explains only 20% of the soil salinity variation. As a result, the fact that irrigation water quality limits soil quality, which was identified at the regional scale, cannot be confirmed.

In order to account for the processes dominant at both the local and the mesoscale, the SahysMod model (Spatial agro-hydro-salinity and groundwater model; http://www.waterlog.info/sahysmod.htm) was chosen to represent the process of soil salinization at the scale of the Drâa oases. The model is appropriate for this aim as it takes into account the groundwater flow system responsible for mesoscale soil salinization. It also takes into account the soil properties and cropping systems that are responsible for the local scale diversification of soil salinity patterns. The model is made up of a network of internal polygons for which calculations are carried out. These are surrounded by external polygons to define boundary conditions. The horizontal flow of groundwater from one polygon to another is simulated using a finite difference approach (SGMP model (Standard Groundwater Model Package) by Boonstra and de Ridder 1981). Water and salts can only be transported horizontally within the saturated zone. The vertical movement of water and salt is calculated from a balance approach, which takes into account

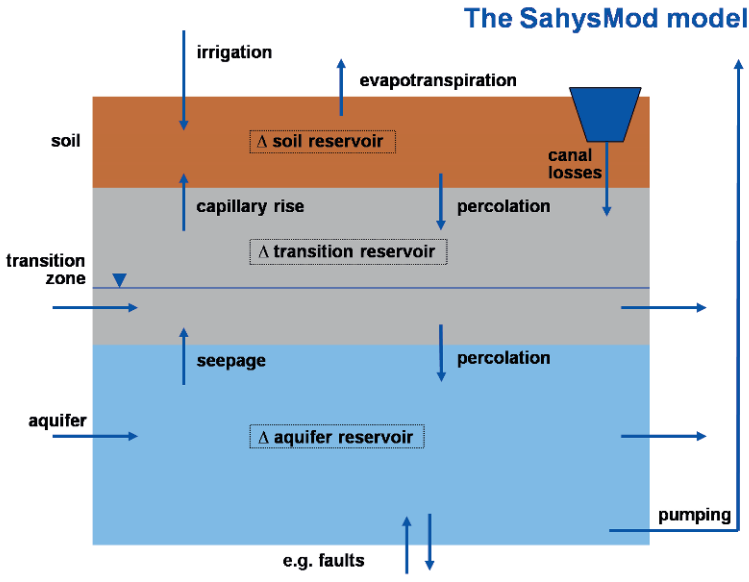

Fig. I-6.2.21: Concept of the vertical water and salt balance within SahysMod.

three reservoirs: the soil, the transition or vadose zone, and the aquifer (see fig. I-6.2.21). For each polygon, different soil and aquifer properties, different irrigation conditions in terms of quality, quantity and source of water, and different cultivated crops can be parameterized to account for local differences. A maximum of four cropping seasons per year can be modeled. Consequently, the climatic conditions as well as the management system (e.g., amount and source of irrigation water) may vary between seasons, but not from year to year.

As spatially distributed information on local scale conditions is rare, model discretization is performed in an abstract way. In each oasis, 70 internal polygons are introduced. Crops are randomly distributed to these polygons according to their percentage of cultivated area (data source: ORMVAO 1995). The main crops in the Drâa oases are wheat, barley, maize, henna, alfalfa, vegetables, and date palms. In the model, they are distinguished via their different water requirements. The crop water requirements are calculated according to the method proposed by Allen et al. (1998; based on the Penman–Monteith approach) using climate data from the IMPETUS meteorological stations and crop coefficients published by *Ministère des travaux publics* (1998). We chose an annual time resolution, i.e., one season per year. Soil properties are extracted from Radanovic (1968a; 1968b; 1968c), Brancic (1968), and Zivcovic (1968). The required parameters are soil depth, total and effective porosity, saturated hydraulic conductivity, leaching coefficient, and initial salt concentration. Aquifer and transition zone parameters are given analogously to the regional groundwater balance model BIL (see above), and the required parameters are the same as for the soil zone. Furthermore, inflow and outflow from the external polygons through the saturated zone can be specified. Fixed flows from one oasis to the next and from the surrounding fractured rocks are parameterized according to the results from BIL. The input of surface water (quantity and quality) depends on the outlets from the reservoir (data source: DRH, *Direction Régionale Hydraulique*). The applied irrigation system is defined via an irrigation efficiency coefficient, i.e., the fraction of the applied water effectively available to the plants. For flood irrigation systems, this coefficient varies between 0.32 and 0.59 and for sprinkler irrigation, between 0.66 and 0.68 (Bos and Nugteren 1990).

In order to analyze the model's sensitivity under the given conditions, the SI_{10} index (Sensitivity Index, see eq. I-6.2.5) was calculated for each input parameter.

$$SI_{10} = \frac{output_{+10\%} - output_{-10\%}}{output_{ref}} \qquad \textbf{(eq. I-6.2.5)}$$

in which

SI_{10} = sensitivity index with 10 % change of input parameter

$output_{+10\%}$ = model output with input parameter increased by 10 %

$output_{-10\%}$ = model output with input parameter decreased by 10 %

$output_{ref}$ = model output with original input parameter

Table I-6.2.5: Sensitivity of model parameters regarding modelled soil and groundwater salinity (GW = groundwater, SI_{10} = Sensitivity Index, see eq. I-6.2.5).

Rank	SI10 soil salinity	Parameter	SI10 GW salinity	Parameter
1	0.36	total amount of irrigation water	0.32	total amount of irrigation water
2	0.29	potential evapotraspiration	0.26	amount of irrigation water from the aquifer
3	0.27	leaching efficiency i the aquifer	0.24	potential evapotranspiration
4	0.25	amount of irrigation water from the aquifer	0.19	leaching efficiency in the aquifer
5	0.19	leaching efficiency in the soil	0.13	initial hydraulic head
6	0.12	initial hydraulic head	0.07	leaching efficiency in the transition zone
7	0.09	salt concentration of incoming canal water	0.07	salt concentration of incoming canal water
8	0.06	leaching efficiency in the transition zone	0.06	inflow of groundwater from external polygons
9	0.05	inflow of groundwater from external polygons	0.04	total porosity of the transition zone
10	0.04	precipitation	0.04	initial salt concentration in the aquifer

Table I-6.2.5 shows the 10 most sensitive input parameters regarding the two model outputs, soil salinity and groundwater salinity.

As expected, the amounts and sources of irrigation water as well as the water demand of crops and atmosphere are the most sensitive parameters for both model outputs. Furthermore, both the salt concentration of irrigation water and the dilution of the groundwater by inflow from external sources, like precipitation and lateral groundwater fluxes, are sensitive parameters. The parameters mentioned so far were estimated based on consistent and well-known approaches (e.g., estimation of crop water demand based on Allen et al. 1998) and on verified model results (groundwater parameters from BIL). The high sensitivity of the leaching efficiency for all three reservoirs is problematic. This parameter depicts the fraction of soil water and salts that are washed out of the soil with the applied irrigation water. The leaching coefficient depends mainly on soil depth, soil texture, and hydraulic conductivity, as well as the presence of cracks and the soil salinity. There is almost no literature that presents values on leaching coefficients, as the parameter is not directly measurable. Available estimations vary between 0.75 and 1 for silty clay loam (UNESCO-UNDP 1970; Van Hoorn 1981). Martinez Beltran (1978) gives values of 0.25 to 0.5 depending on soil salinity and depth. This high degree of uncertainty regarding the leaching efficiency together with the high model sensitivity toward the leaching coefficient leads to considerable uncertainty in the modeling process.

Despite this limitation, the model was set up for the six oases with the above described parameterization. The leaching coefficients are taken from the literature mentioned above (0.85, 0.9 and 0.95 for soil, transition zone, and aquifer respectively). Initial conditions regarding groundwater and soil are taken as reported for 1968 (Bouidida 1990). The mean climatic conditions and reservoir outlets for the period 1968 – 1998 are used (data source: DRH). The model was run for a 30-year period, and results for the year 1980 are compared to measured data from Bouidida (1990; see fig. I-6.2.22). Results for the Mezguita oasis show a good agreement between modeled and measured data, although salinity is slightly underestimated by the model. This underestimation might be a result of the model concept, in which climatic and management conditions are constant over the whole modeling period. Thus, only intra-annual, not interannual variation is reflected in the model, and the effect of dry and wet years is averaged.

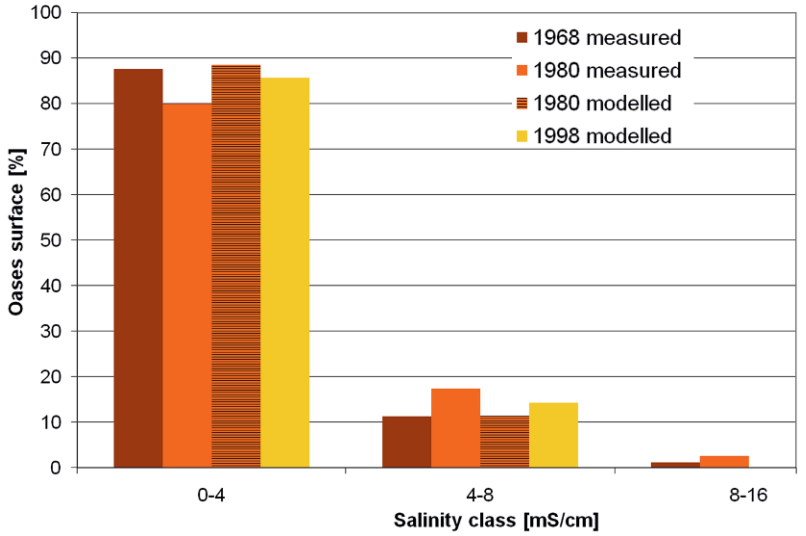

Fig. I-6.2.22: Comparison of modelled and measured soil salinity in the oasis of Mezguita (for location of the oasis cf. fig. I-3.2.3).

The model predicts a slight increase of salinity up to 1998. The system seems well reflected by the model as the increase is not too high. This was not expected as the flood irrigation system provides much water to the soils, allowing for the leaching of salts. A more dramatic increase in soil salinity is expected when the irrigation system is changed toward drip irrigation, as recently propagated by the local agricultural service ORMVAO.

I-6.2.6 Soil erosion by water: Processes and simulations

Data on soil erosion by water is sparse in the Drâa catchment. The Moroccan Hydrological Service (*Direction Régionale Hydraulique*, DRH) carried out bathymetric surveys at the Mansour Eddahbi reservoir in 1982, 1988, 1994, and 1998 (see fig. I-6.2.23). In 1972, at the time of the reservoir's construction, it had a capacity of 583 Mm³. Approximately 25% of its capacity was lost by 1998, with about 439 Mm³ remaining capacity. This results in an estimated mean erosion rate in the Upper Drâa catchment of 5.6 t/ha/a. Of course, this figure only depicts the part of the detached soil that arrives at the reservoir. Thus, it gives information neither on the on-site loss of soil nor on its spatial distribution within the catchment. But this information is crucial for an efficient management of anti-erosive measures, both to protect the soil resources on-site and the reservoir off-site. Further information is thus needed on the extent and distribution of soil erosion by water.

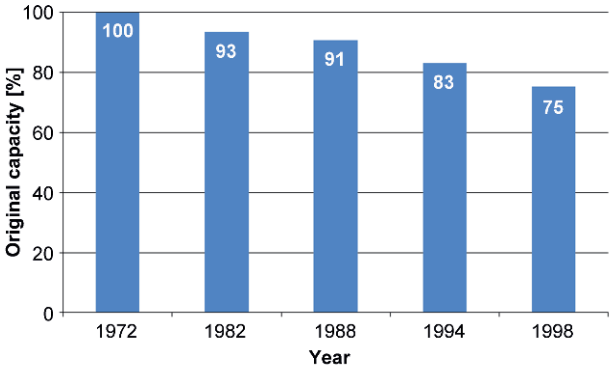

Fig. I-6.2.23: Silting of the Mansour Eddahbi Reservoir since its construction up to the last bathymetric survey in 1998 (Data source: DRH).

In semi-arid regions, soil erosion measurement is difficult due to the occurrence of extreme events that tend to destroy measurement instruments (Coppus and Imeson 2001). Furthermore, precipitation events are extremely rare, so it is possible for no event to occur at the measured site for several years. For these reasons, no Wischmeier plots were installed in the Drâa catchment.

In a badland area in the basin of Ouarzazate two gullies were instrumented with a total of 147 erosion pins. The region is characterized by gullies incised up to three meters, but an overall flat relief. The soils are highly erodible due to high silt and fine sand contents and high sodium adsorption ratios. Solonetz soils appear frequently. The measurement period was from December 2004 to May 2008. As it was very likely that the pins would be removed by the local people when visible in the field, they were completely embedded into the soil. Due to this method of installation, not all of the pins were recovered, thus limiting the quality of the esti-

mation. Nevertheless, when assuming that those pins where soil was removed were recovered and soil removal is assumed to be zero for the other pins, a mean erosion rate of 28.4 t/ha/a was estimated from these data (see table I-6.2.6). The estimated erosion rate is highest for the first period (Dec 04 – Nov 05), although both precipitation sum and daily rainfall intensities were lower than in the other periods. The explanation for the high soil loss rate is probably the high 15 minute precipitation intensity. This indicates that the daily precipitation sum might not be the appropriate predictor for high soil loss rates.

Table I-6.2.6: Soil loss rate retrieved from erosion pins in a badland area in the basin of Ouarzazate (Precipitation data from the IMPETUS climate station Trab Labied, see sect. I-4.2).

	Dec 04 - Nov 05	Nov 05 - Mar 07	Mar 07 - May 08	Mean
Soil loss [cm]	0.23	0.18	0.21	0.21
Soil loss [t/ha]	35.20	27.50	30.80	31.20
Soil loss [t/ha/a]	38.00	19.60	27.40	28.40
Precipitation [mm]	66.30	173.80	187.80	
Most intense event [mm/day]	17.00	30.80	26.20	
Most intense event [mm/15min.]	9.80	1.70	6.00	

As the data described above is much too uncertain and much too sparse to draw conclusions on the erosion risk within the catchment, it was decided that a risk assessment using a physically based model should be carried out. The data availability in the catchment limits the applicability of an event-based model, which requires a vast amount of input data. However, the aim of this study is to carry out a long-term assessment and to appraise the influence of long-term climate and land use changes on the existing system. Thus, the PESERA model (Pan European Soil Erosion Risk Assessment) was chosen, as it aims at a long-term assessment of soil erosion risk in large, data-sparse basins (Kirkby et al. 2003). It calculates mean long-term erosion rates at a monthly interval for a single representative year. PESERA was developed in the homonymous project funded by the European Commission[1] in which semi-arid regions under Mediterranean climate have been considered. It is a physically based, spatially distributed soil erosion model

[1] http://eusoils.jrc.it/ESDB_Archive/pesera/pesera_download.html
http://www.kuleuven.ac.be/geography/frg/leg/projects/pesera/index.htm
http://www.geog.leeds.ac.uk/groups/pesera/

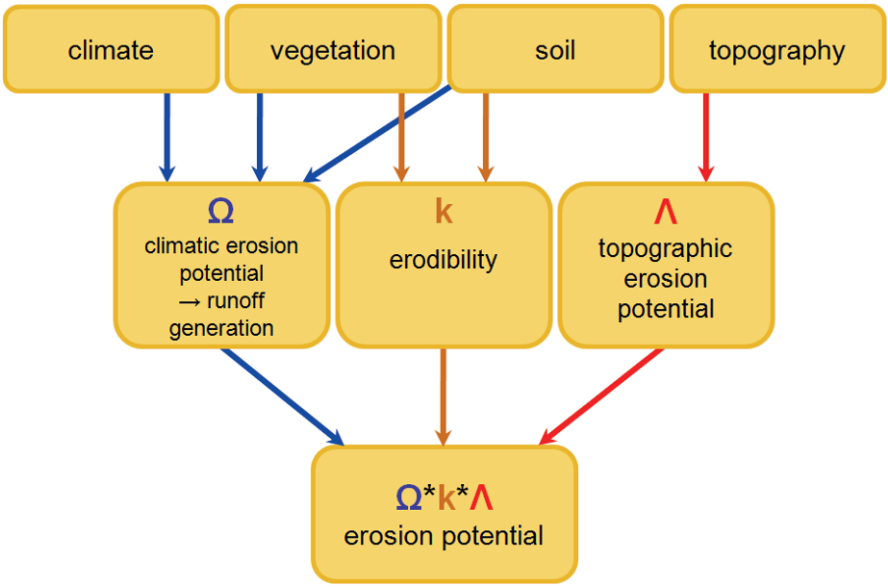

Fig. I-6.2.24: General structure of the PESERA model.

designed to carry out an erosion risk assessment for the whole of Europe at a spatial resolution of 1 km². The model combines the effects of topography, soil, vegetation, and climate for an estimation of runoff, vegetation cover, and erosion under long-term conditions (see fig. I-6.2.24).

Hillslope erosion and sedimentation are predicted, which form the net delivery of the eroded material to the hillslope base. Channel delivery processes and channel routing are not considered (Kirkby et al. 2008). The model is adapted to large basins and coarse scales. It is a raster model with one cell representing one entire slope. It has the capacity for simulating scenarios of land use and Climate Change as it implies a vegetation growth routine that adjusts vegetation cover to given climatic conditions. Precipitation is partitioned into infiltration excess runoff, saturation excess runoff, snowmelt, evapotranspiration and changes in soil moisture storage. The occurrence of infiltration excess overland flow depends on a runoff threshold derived from soil characteristics, organic matter, and vegetation cover. This concept does not take into account antecedent soil moisture and thus produces only small errors in (semi-) arid zones where soils tend to dry out between precipitation events. In order to reproduce long-term conditions, mean monthly climate data is used and daily rainfall is integrated using a gamma function to display the monthly frequency distribution of rainfalls. Due to this coarse time resolution of climate data, an infiltration calculation based on the Richards' equation (e.g., via the Green-Ampt formulation) is not possible, and the runoff threshold approach was chosen. The principle model concept is to first establish stable hydrological and vegetation conditions under the given climate and subsequently

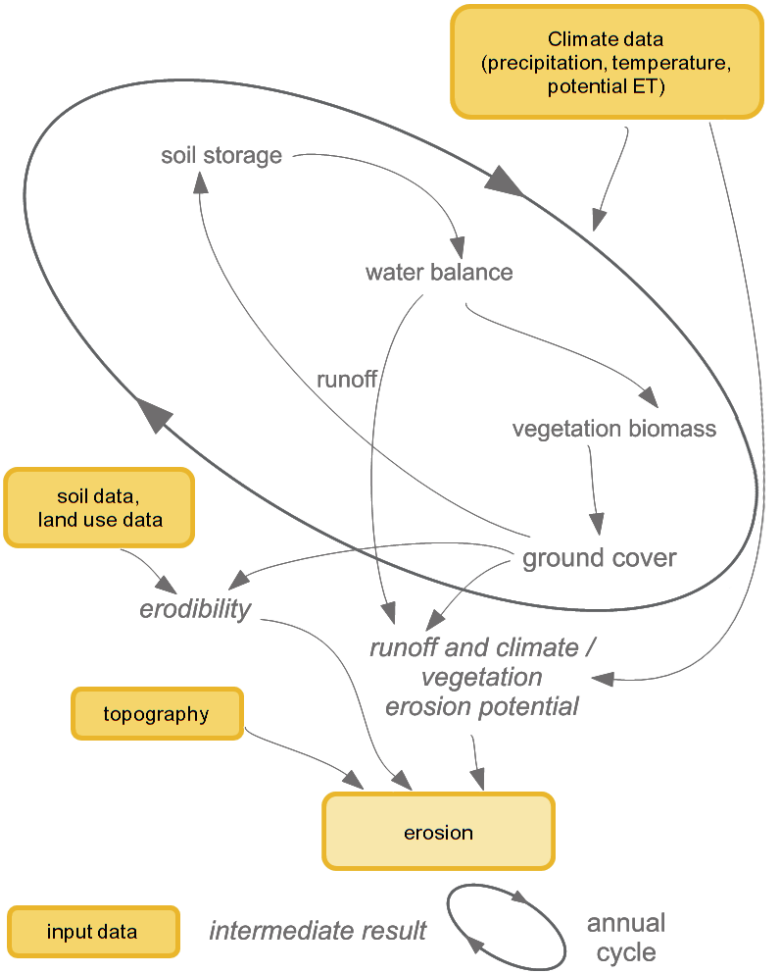

Fig. I-6.2.25: Principle flow scheme of the PESERA model (altered from Kirkby et al. 2003).

use these conditions to calculate mean monthly erosion rates. This is reached by iteratively solving the equations to calculate hydrological parameters and vegetation-related parameters in an annual cycle until stable conditions exist (Kirkby et al. 2008). The equations are solved independently for each raster cell, and neighborhood relationships are not considered. Figure I-6.2.25 shows the principle flow scheme of the model.

PESERA was chosen in this work, as it requires a manageable amount of input data at a rather coarse spatial and temporal resolution. The data availability in the Drâa catchment is limited, and especially the regionalization of climate and soil data is difficult due to the highly heterogeneous terrain. Furthermore, its applicability in large semi-arid basins has been proven. A physically based model was

preferred against an empirical model, like the USLE (Universal Soil Loss Equation) and its enhancements, as the empirical equations have not been adapted to north-African (semi-) arid conditions due to a sparse data base.

The spatial discretization of the model is ruled by the mean slope length, as each raster cell represents a slope. In the Drâa catchment, the mean slope length was computed from a DEM to be 240 m, thus a raster resolution of 250 x 250 m was chosen. Topographic input data are calculated from the DEM provided by the NASA Shuttle Radar Topography Mission (SRTM)[2]. The required soil input data was determined with the help of pedotransfer functions (Gobin and Govers 2002; Le Bissonnais 2005; Antoni et al. 2006) from maps of soil properties provided by the IMPETUS project (A. Klose 2008 and 2009). The soil property maps were derived following the CORPT approach (Jenny 1941), which assumes soils to be products of the environment in which they are formed (C=climate, O=organisms, R=relief, P=parent material, T=time). The available environmental information was statistically related to the soil properties using multiple linear regression, including dummy variables based on 211 soil profiles throughout the Drâa catchment (A. Klose 2009). Information on vegetation was extracted from the classification of a Landsat scene combined with habitat modeling together with expert judgment (see sect. I-7.2). The vegetation growth subroutine of the PESERA model calculates the potential natural vegetation cover. However, as the main land use in the Drâa catchment outside the oasis is pastoral, the potential vegetation cover is substantially reduced. To account for this grazing impact, a map of vege-

Table I-6.2.7: Sensitivity index (SI_{10}, see eq. I-6.2.5) for different model input parameters regarding modelled erosion (evaluation of sensitivity following de Roo 1993).

Parameter	SI_{10}	evaluation
Erodibility	805.262	very high
Monthly mean precipitation per rainy day	0.623	high
Standard deviation of elevation	0.200	medium
Monthly precipitation	0.107	medium
Coefficient of variation of precipitation per rainy day	0.060	medium
Crusting sensitivity	0.048	low
Surface roughness storage	0.025	low
Soil water storage capacity	0.021	low
Soil hydrological scale depth	0.012	low
Mean monthly temperature	0.005	low
Rooting depth	0.004	low
Monthly ET_p	0.003	low
Available water capacity 0-30 cm depth	0.003	low
Available water capacity 30-100 cm depth	0.000	low
Monthly temperature range	0.000	low
Monthly reduction of surface roughness storage	0.000	low

[2] http://www2.jpl.nasa.gov/srtm/

tation reduction was established based on the grazing exclusion experiments carried out by Finckh (see sect. I-7.2). Finally, maps of climatic input data were derived based on data from meteorological stations (DRH and IMPETUS) related to terrain altitude.

Before model calibration, a sensitivity analysis should be carried out to assess and evaluate the influence of model input parameters on the modeled erosion rate. The sensitivity index SI_{10} (see eq. I-6.2.5; de Roo 1993) was used to rank the input parameters according to their influence on the model output (see table I-6.2.7).

In the original parameterization, the model underestimated surface runoff in comparison with the results of the hydrological model SWAT (Soil and Water Assessment Tool; see above). Thus, the rooting depth, soil water storage capacity, soil hydrological scale depth, crusting sensitivity and erodibility input parameters were adjusted in order to enhance runoff. Figure I-6.2.26 shows the calibrated model result for surface runoff compared to the SWAT results. The temporal dynamic and the order of magnitude agree well between the models. The surface runoff modeled in the upper catchment totals about 216 Mm³, and the groundwater recharge totals about 155 Mm³. Therefore, a total long-term mean 371 Mm³ of water reaches the Mansour Eddahbi reservoir annually. From 1980 – 2000, the mean measured discharge to the reservoir was 404 Mm³. Thus, PESERA seems to underestimate total discharge by approximately 8%, not taking into account the abstractions for irrigation upstream of the reservoir. This leads to the assumption of a possible overestimation of actual evapotranspiration.

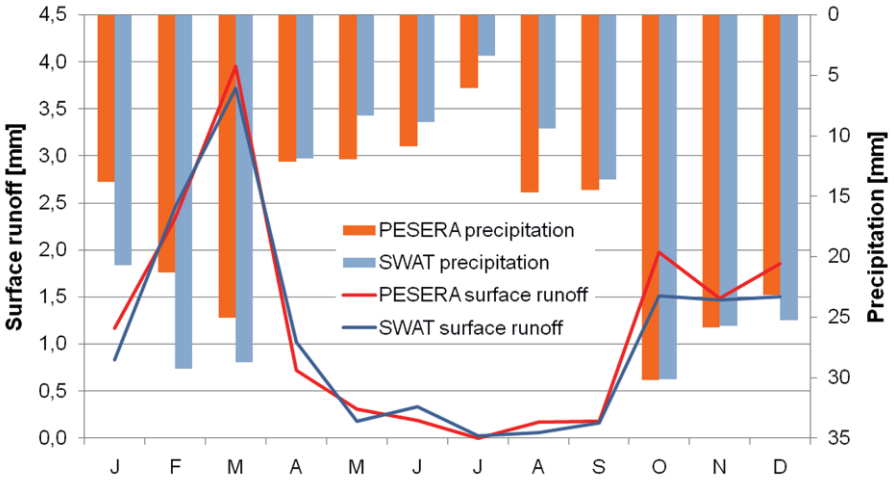

Fig. I-6.2.26: Comparison of modelled discharge using the SWAT and the PESERA models.

Furthermore, calibrated model results were compared to field estimations of vegetation density. Fritzsche (personal communication) carried out field estimations of vegetation cover at 87 vegetation plots throughout the catchment in spring

(March and April) and 60 vegetation plots in autumn (September) 2007. The data from the field estimations as well as the modeled vegetation cover were classified into five classes (0–5%, 5–15%, 15-30%, 30–60% and >60% vegetation cover) and compared to each other. Although the temporal and spatial scales differ considerably between the field data (one single year, 1 m² plot) and the modeled data (long-term estimation, 250 x 250 m pixel), the data correspond well to the modeled PESERA vegetation cover (see fig. I-6.2.27). For both spring and autumn, the model calculated approximately 85% of the plot locations having the same vegetation cover class or the neighboring class as estimated from the field data.

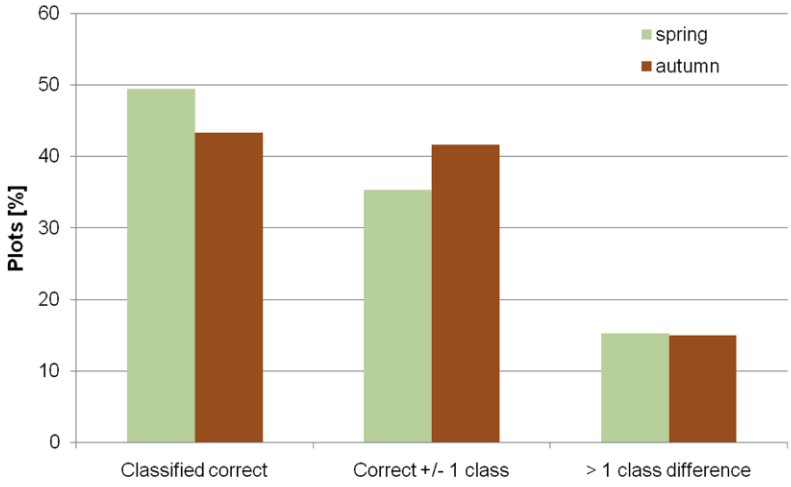

Fig. I-6.2.27: Comparison of modelled (calibrated) and measured vegetation cover in spring and autumn 2007 (measured vegetation data from Fritzsche (personal communication); for class definition and sample numbers see text).

Actual evapotranspiration (ET_a) is the most important factor of the water balance, accounting for 95% of the precipitation averaged over the whole catchment (see fig. I-6.2.28). In the High Atlas, it is lower due to lower temperature and a higher relative humidity. In the catchment's extreme south, it is lower due to lower vegetation cover and the resulting higher surface runoff. Thus, the surface runoff shows more or less the opposite spatial distribution to ET_a (see fig. I-6.2.28). Only in the High Atlas does groundwater recharge play a significant role. This corresponds well with the findings of Cappy (2006), who showed with the help of isotopic tracers that the mean recharge altitude of groundwater found in the Basin of Ouarzazate is 2400 – 2900 m asl. Therefore, the main recharge area lies in the High Atlas.

Mean soil loss in the Drâa catchment in the calibrated reference simulation is estimated to be 19.2 t/ha/a in the whole catchment and 28.7 t/ha/a in the upper catchment (see fig. I-6.2.28). This figure is considerably higher than the input to the reservoir calculated from the bathymetric survey data (5.6 t/ha/a). It is low,

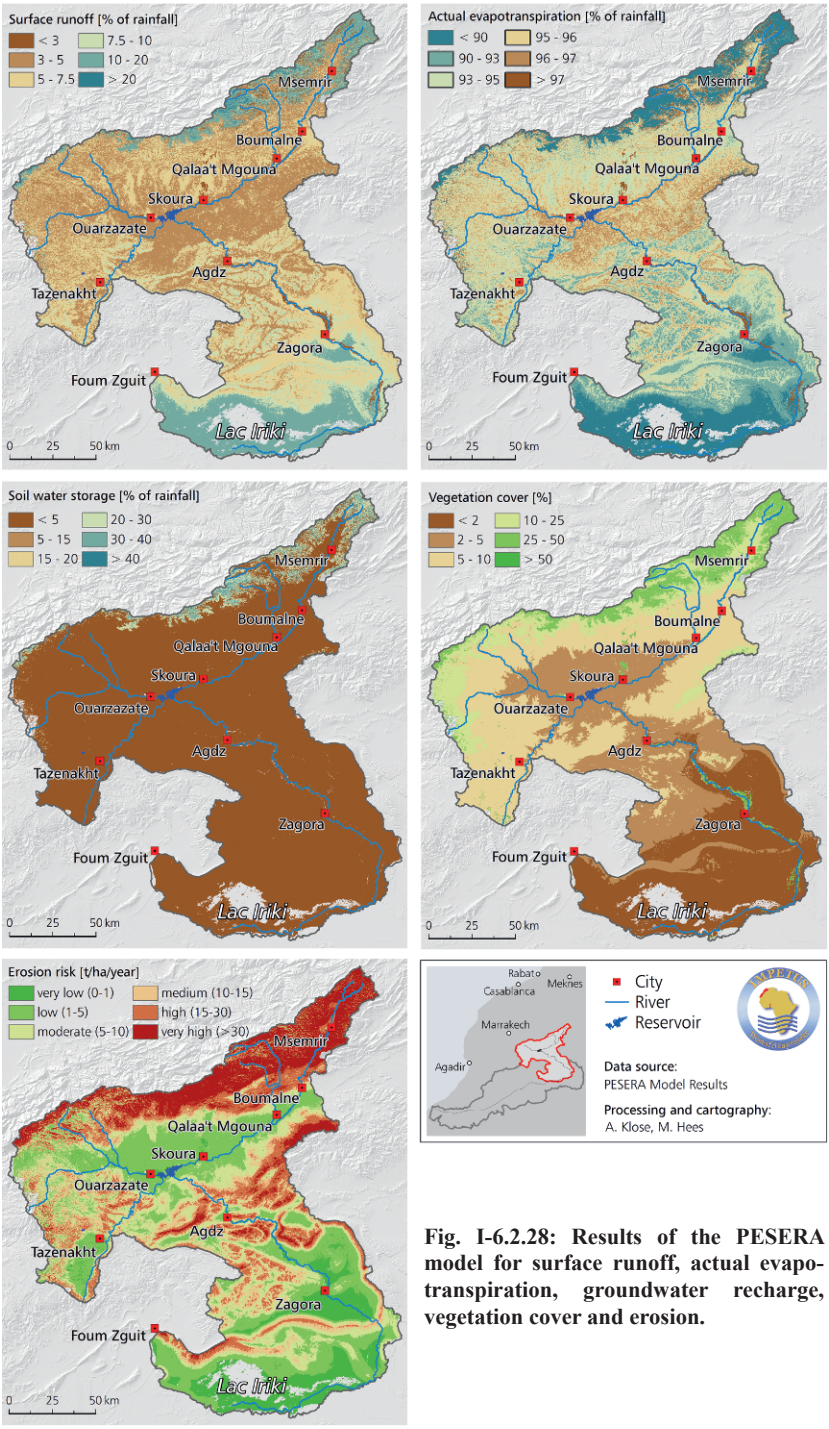

Fig. I-6.2.28: Results of the PESERA model for surface runoff, actual evapotranspiration, groundwater recharge, vegetation cover and erosion.

however, compared to *Haut Commissariat aux Eaux et Forets et la Lutte contre la Desertification* (2007), who calculated 99.9 t/ha/a for the Upper Drâa catchment by applying the RUSLE (Revised Universal Soil Loss Equation). The discrepancy between erosion rates modeled with PESERA and input to the reservoir can be explained by the model concept explicitly excluding sediment deposition on the flow path. From the modeled data and the bathymetric survey data, one can calculate a mean sediment delivery ratio (SDR) of 19.5% for the Upper Drâa catchment. *Haut Commissariat aux Eaux et Forets et la Lutte contre la Desertification* (2007) propose to calculate the sediment delivery ratio as a function of flow length and altitude differences (following Hession and Shanholtz 1988) within sub-catchments (see eq. I-6.2.6).

$$SDR = \frac{10 * ED}{FL} \qquad \textbf{(eq. I-6.2.6)}$$

in which

SDR	=	Sediment Delivery Ratio
ED	=	Elevation Difference between point and catchment outlet
FL	=	FlowLength to catchment outlet

Applying this approach to the upper catchment results in a mean SDR of 9.6% combined with the PESERA erosion rate, a sediment input to the reservoir of 2.8 t/ha/a is calculated. Thus, the order of magnitude of the erosion calculated with the help of PESERA seems reasonable. As spatially distributed data for comparison are missing, a model-model comparison was chosen to evaluate the results. The spatial distribution of modeled erosion corresponds well to the results of the RUSLE (Haut Commissariat aux Eaux et Forets et la Lutte contre la Desertification 2007). Although the RUSLE results are many times higher than the PESERA results, the relative relation among the subcatchments seems to be similar (r^2=0.6, n=23). This hints at a plausible spatial distribution of erosion modeled with PESERA.

The PESERA results indicate erosion hotspots in the mountainous zones of the High Atlas and Antiatlas. Especially high erosion rates (> 200 t/ha/a) are calculated for the Skoura Mole, the M'Goun chain, and the extreme Northwest of the High Atlas (see fig. I-6.2.28). This is because of the extraordinarily high relief energy in these zones with the highest overall precipitation amount. Also, for topographic reasons, the mountain chains in the Antiatlas and the Saharan Foreland show higher erosion rates than their surrounding areas. The flat basin areas (Basin of Ouarzazate, Tazenakht, and intra-mountainous basins in the Saharan Foreland) feature low erosion rates of less than 5 t/ha/a (see fig. I-6.2.28). Furthermore, the oases exhibit very low erosion rates due to their high vegetation cover (< 1 t/ha/a). In the field, one can observe that bank erosion is a common phenomenon, especially in the silty flood deposits of the oasis. This process is not accounted for in the PESERA model. Therefore, assuming that the oasis areas are well protected

from erosion based on the PESERA results could be misleading, especially for the arable land directly adjacent to the rivers.

When the on-site effects of erosion are of interest for planning anti-erosive measures, the actual soil depth as well as the skeleton content has to be taken into account. The same erosion rate may be uncritical for profound soils featuring low skeleton contents, but it can turn shallow, stony soils into non-arable land. Therefore, the remaining soil depth and the fine soil content after 15 years of erosion was calculated from the PESERA erosion rates assuming a bulk density of 1.5 g/cm³ (see fig. I-6.2.29). It is obvious that the on-site effects on soil depth are worst in the mountainous zones, where soils are already shallow and erosion rates are high. This is especially the case in the Basins of Ouarzazate and Tazenakht, where the soil depth remains sufficiently high for agricultural use within the next 15 years. This is advantageous, as these zones are of interest for agricultural use due to gentle slopes and good accessibility. These regions, however, suffer from high skeleton contents in the soils, and this problem will be further aggravated (see fig. I-6.2.29). To protect on-site soil resources, the mountainous zones should be a focal area for possible anti-erosive measures. The latter areas are not favored, however, for possible agricultural use, due to steep slopes, shallow soils and very high skeleton contents. Therefore, to protect areas for further extension of agricul-

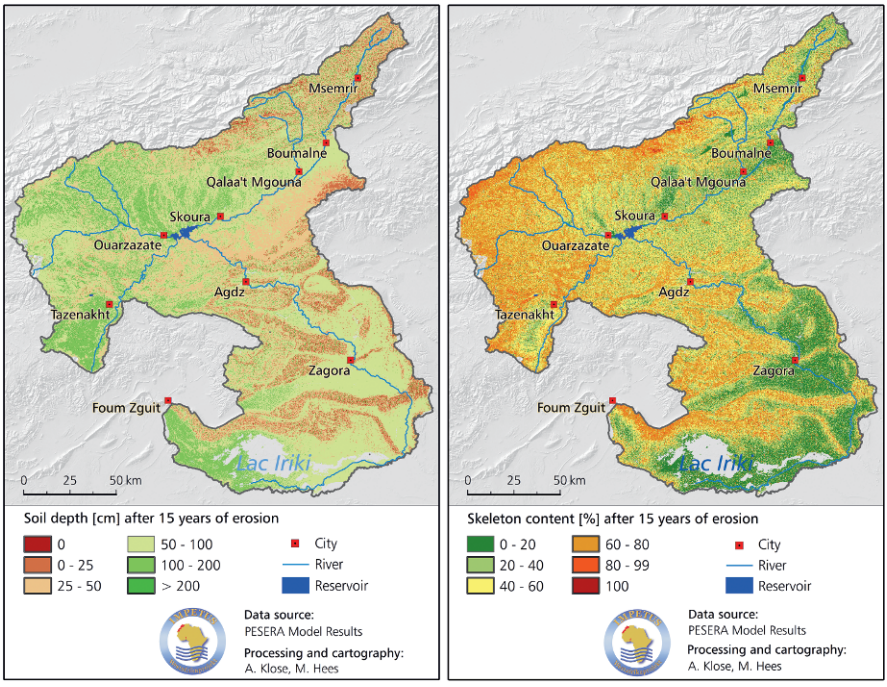

Fig. I-6.2.29: Soil depth and skeleton content after 15 years of erosion according to the PESERA model results.

ture, it is also recommended that anti-erosive measures should be established in the basin areas. These suffer more from high skeleton contents than from shallow soils. Soil fertility in the basin areas is naturally low, so the application of fertilizers is still essential.

The modeled erosion rates were combined with the distributed sediment delivery ratio for the upper catchment. Using this approach, the erosion rates can be interpreted as a threat to the Mansour Eddahbi reservoir. The high erosion rates throughout the High Atlas are less important for reservoir sedimentation due to the long flowpaths from the source areas, but it may endanger the downstream infrastructure. The Skoura Mole area seems to be an endangered area for both on-site and off-site erosion threat as the transport path to the reservoir is relatively short and erosion rates are high. Therefore, focus should be put on this zone when planning anti-erosive measures that concentrate on the protection of the reservoir.

I-6.2.7 Conclusions

The hydrological and erosional processes in the Drâa valley have been analyzed and quantified. IMPETUS has obtained a thorough understanding of the processes and their spatio-temporal variability.

Concerning snow hydrology, two different model concepts were successfully applied to the High Atlas Mountains. Simulations with the physically based point scale model UEB confirmed the process understanding of snow ablation. These simulations also showed that sublimation is one important factor in higher elevations with favorable conditions during winter (near or subzero air temperature, low humidity, and enhanced radiation). Satellite images at moderate resolution (463 m, MODIS) were used to monitor the temporarily highly dynamic and spatially heterogeneous snow cover patterns. The resulting information was used to simulate discharge from snowmelt at the M'Goun subcatchment with the conceptual regional scale model SRM. Based on the SRM results, the PRO-RES monitoring tool was developed to simulate runoff for the whole Upper Drâa catchment. Both SRM and PRO-RES were successfully calibrated and validated.

Other hydrological processes were analyzed at the local and the regional scale. Soil hydrology at the local scale varies strongly due to different infiltration and water holding capacities. At the regional scale, the base flow transmission losses, the snow dynamic and irrigation processes govern the hydrological behavior. The SWAT model is able to represent these processes. Irrigation abstractions are externally preprocessed using the Penman-Monteith approach. Special emphasis was put on precipitation regionalization as a strong gradient dependent on altitude was depicted. The model was successfully calibrated and validated for the Upper Drâa catchment.

The results of the studies on aquifer setting, regional groundwater dynamics, and hydrogeochemistry reveal a conclusive image of the regional aquifer system

of the Middle Drâa valley. The existing expertise has not only been extended by more data, but by new findings on groundwater evolution and the aquifer system, especially in terms of the afflux from the aquitard system. Consequently, the assessment of groundwater availability in the oasis aquifers is achieved. The groundwater balance model BIL was developed and successfully applied to the Middle Drâa valley. The lack of data in piezometry, aquifer properties, and groundwater chemistry is precisely identified in order to fill these gaps in the future and to support groundwater monitoring and management.

At the regional scale, a clear increase in groundwater and soil salinity from the Mansour Eddahbi reservoir toward the Saharan Foreland can be depicted. This gradient is governed by increasing aridity as well as the influence of irrigation agriculture. At the local scale, many processes superpose, and salinity patterns depend on irrigation, soil properties, usage history, and crop type. The SahysMod model is able to cope with these processes at both scales and was successfully applied to the oases of the Middle Drâa valley.

Concerning soil quantity and fertility, soil erosion is a severe problem at the local scale as well as the regional scale due to the siltation of the valley floors and the reservoir. Because PESERA is a mechanistic model that considers feedback mechanisms between soil water dynamics, vegetation, and soil erosion, the results indicate areas at risk, although local scale measurements are not available. These areas should be observed and, if possible, management strategies should be developed to minimize erosion risk.

The PRO-RES and SWAT hydrological models, the groundwater balance model BIL, the salinity model SahysMod, and the PESERA soil erosion model represent well the relevant processes. They thus proved their ability to successfully process the scenario calculations introduced in part II of this book (see sect. II-5.2 and sect. II-5.3).

References

Abbaspour KC, Johnson CA, van Genuchten MT (2004) Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure. Vadose Zone J 3(4):1340-1352

Antoni V, Thorette J, Zaidi N, le Bissonais YL , Laroche B, Barthès S, Daroussin J, Arrouays D (2006) Modélisation de l'aléa érosion pour une région méditerra-néenne francaise à deux échelles différentes: aux échelles du 1/1.000.000 et du 1/250.000. Water Management and Soil Conservation in Semi-Arid Environments - the 14th Conference of International Soil Conservation Organization, Marrakech, Morocco. http://www.tucson.ars.ag.gov/isco/index_files/Page416.htm. Accessed 21 October 2009

Aoubouazza M, El Meknassi YE (1996) Hydrologie et Hydrogéologie du bassin de la Feija de Zagora (Province Ouarzazate). Étude sur la lutte contre la désertification dans la vallée moyen de l'Oued Drâa. Direction du Développement et de la Gestion de l'Irrigation. Rabat

Allen RG, Jensen ME, Wright JL, Burman RD (1989) Operational Estimates of Reference Evapotranspiration. Agron J 81(4):650

Allen RG, Pereira LS, Raes S, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Papers 56. FAO, Rome

Arnold JG, Allen PM, Bernhardt G (1993) A Comprehensive Surface-Groundwater Flow Model. J Hydrol 142(1-4):47-69

Bouidida A (1990) Salinité des eaux de la vallee du Drâa - situation actuelle et evolution. Diploma thesis, University Hassan II, Rabat

Boonstra J, de Ridder NA (1981) Numerical Modelling of Groundwater Basins. ILRI publ. 29. International Institute for Land Reclamation and Improvement, Wageningen

Bos MG, Nugteren J (1990) On irrigation efficiencies. ILRI publ. 19. International Institute for Land Reclamation and Improvement, Wageningen

Brancic B (1968) Sols de la palmeraie de Fezzouata. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Cao WZ, Bowden WB, Davie T, Fenemor A (2006) Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability. Hydrol Process 20(5):1057-1073

Cappy S (2006) Hydrogeological Characterization of the Upper Drâa Catchment (Morocco). Doctoral thesis, University of Bonn, Bonn http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2007/cappy_sebastien/. Accessed 21 October 2009

Chamayou J (1966) Hydrogéologie de la Vallée du Dra Moyen. Doctoral thesis

Chamayou J, Combe M, Dupuy J-C (1977) Moyenne Vallee du Dra. In: Devision de la Geologie (ed) Ressources en eau du Maroc, Tome 3, Domaines atlasique et sud-atlasique, Notes et Mémoires du Service Géologique 231. Rabat

Chaponnière A, Boulet G, Chebouni A, Aresmouk M (2008) Understanding hydrological processes with scarce data in a mountain environment. Hydrol Proc-ess 22:1908-1921

Compagnie Africain de Géophysique (ed) (1947) Prospection electrique au Foum Takkat. Siège Social, Casablanca

Coppus R, Imeson AC (2001) Extreme events controlling erosion and sediment transport in a semi-arid sub-Andean valley. Earth Surf Proc Land 27(13):1365-1375

de Roo ADJ (1993) Modelling surface runoff and soil erosion in catchments using geographical information systems, Validity and applicability of the "ANSWERS" model in two catchments in the loess area of South Limburg (the Netherlands) and one in Deven (UK). Netherlands Geographical Studies 157

Destombes J (1985) Ordivician. In: Holland CH (ed) Lower Palaeozoic of north-western and west central Africa. 1. Edition. Wiley, Chichester

Doukkali MR (2005) Water institutional reforms in Morocco. Water Policy 7:71-88

DRE (Devision des Ressources en Eau) (ed) (1976) Étude des ressources en eau souterraine de l'Anti-Atlas Central (Région d'Ouarzazate). Programme spécial de recherche d'eau dans les zones déshéritées. Direction de l'Hydraulique, Ministère des Travaux Publics et des Communications. Royaume du Maroc. Rabat

DRH (Direction de la Région Hydraulique d'Agadir de Souss Massa et Drâa) (ed) (2001) Étude d'approvisionnement en eau potable des populations rurales de la province de Zagora, Mission 1 : Analyse de la situation actuelle du service de l'eau et collecte des données de base, Volume 2 - Etude des ressources en eau. Direction de la Recherche et de la Planification, Direction Générale de l'Hydraulique, Ministère de l'Equipement, Royaume du Maroc. Rabat

Dunkerley DL (2008) Bank permeability in an Australian ephemeral dryland stream: variation with stage resulting from mud deposition and sediment clogging. Earth Surf Proc Land 33(2):226-243

EI-Hames AS, Richards KS (1994) Progress in arid-lands rainfall-runoff modelling. Progress in Physical Geography 18(3):343-365. doi:10.1177/030913339401800304

Flerchinger GN, Cooley KR (2000) A ten-year water balance of a mountainous semi-arid watershed. J Hydrol 237:86-99

Fontaine TA, Cruickshank TS, Arnold JG, Hotchkiss RH (2002) Development of a snowfall-snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). J Hydrol 262(1-4):209-223. doi:10.1016/S0022-1694(02)00029-X

Gobin A, Govers G (2002) Pan European Soil Erosion Risk Assessment - Second annual report 2001-2002. The European Commission 5th framework programme. http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_cd/pdf/Pesera2AnnRep.pdf. Accessed 21 October 2009

Griffiths GA, Clausen B (1997) Streamflow recession in basins with multiple water storages. J Hydrol 190(1-2):60-74

Haut Commissariat aux Eaux et Forets et la Lutte contre la Desertification (ed) (2007) Elaboration du dossier de base pour l'etude d'amenagement en amont du barrage d'El Mansour Eddahbi

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, The U. S. Geological Survey Modular Ground-Water Model-User Guide to Modularization Concepts and the Ground-Water Flow Process. Open-file Report. U. S. Geological Survey 92

Harmel RD, Cooper RJ, Slade RM, Haney RL, Arnold JG (2006) Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Trans ASAE 49(3):689-701

Heidecke C, Kuhn A, Klose S (2008) Water pricing options for the Middle Drâa River Basin in Morocco. AfJARE 2(2):170-187

Helg U, Burkhard M, Cartig S, Robert-Chaurre C (2004) Folding and inversion tectonics in the Anti-Atlas of Morocco. Tectonics 23:1-17

Hernandez M, Miller SN, Goodrich DC, Goff BF, Kepner WG, Edmonds CM, Jones KB (2000) Modeling Runoff Response to Land Cover and Rainfall Spatial Variability in Semi-Arid Watersheds. Environ Monit Assess 64:285-298

Hession WC, Shanholtz VO (1988) A geographic information system for targeting nonpoint-source agricultural pollution. J Soil Water Conserv 43(3):264-266

Ismat Z (2008) Folding and kinematics expressed in fracture patterns: An example from the Anti-Atlas fold belt, Morocco. J Struct Geol 30:1396-1404

Jenny H (1941) Factors of soil formation. A system of quantitative pedology. Dover Publications Inc., New York

Ji X-B, Kang E-S, Chen R-S, Zhao W-Z, Zhang Z-H, Jin B-W (2007) A mathematical model for simulating water balances in cropped sandy soil with conventional flood irrigation applied. Agr Water Manage 87(3):337-346

Khazaei E, Spink AEF, Warner JW (2003) A catchment water balance model for estimating groundwater recharge in arid and semi-arid regions of south-east Iran. Hydrogeol J 11(3):333-342

Kleindienst H, Pfister M, Baumgartner MF (1999) Pre-operational snowmelt fore-casting based on an integration of ground measurements, meteorological forecasts and satellite data. In: Tranter M (ed) Interactions Between the Cryosphere, Climate and Greenhouse Gases. IAHS Publication 256:81-89

Kirkby M, Gobin A, Irvine B (2003) PESERA model strategy, land use and vegetation growth. http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_cd/pdf/DL5ModelStrategy.pdf. Accessed 21 October 2009

Kirkby M, Irvine B, Jones RJA, Govers G, the PESERA Team (2008) The PESERA coarse scale erosion model for Europe. I. - Model rationale and im-plementation. Eur J Soil Sci 59(6):1293-1306

Klose A (2008) Soil Properties in the Drâa Catchment. In: Schulz O, Judex M (eds) (2008) IMPETUS-Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 33-36. Department of Geography, University of Bonn, Bonn

Klose A (2009) Soil characteristics and soil erosion by water in a semi-arid catchment (Wadi Drâa, South Morocco) under the pressure of global change. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/2009/1959/1959.htm Accessed 25 November 2009

Klose S, Reichert B, Lahmouri A (2008) Management options for a sustainable groundwater use in the Middle Drâa Oases under the pressure of climatic changes. In: Zereini F, Hoetzl H (eds) Climatic Changes and Water Resources in the Middle East and North Africa. Springer, Berlin

Lahlou A (1988) The silting of Moroccan Dams. In: Bordas MP, Walling DE (eds) Sediment Budgets. IAHS Publication 174:71-77

Lane LJ (1983) Chapter 19: Transmission Losses. In: Soil Conservation Service (ed) National Engineering Handbook, Section 4: Hydrology, pp. 19-21. U.S. Government Printing Office, Washington DC

Le Bissonnais YL (2005) Pan-European soil crusting and erodibility assessment from the European Soil Geographical Database using pedotransfer rules. Adv Environ Monit Modell 2(1):1-15

Le Houérou HN (1996) Climate change, drought and desertification. J Arid Envi-ron 34(2):133-185

Margat J (1958) Le probleme de l'eau et les etudes hydrgéologique a entreprendre dans la Vallee du Drâa

Martin S (2006) Influence du tourisme sur la gestion de l'eau en zone arid – Exemple de la vallée Du Drâa (Maroc). Doctoral thesis, University of Lausanne, Lausanne

Martinec J (1975) Snowmelt-Runoff model for stream flow forecasts. Nord Hy-drol 6(3):145-154

Martinec J, Rango A, Roberts R (1998) Snowmelt Runoff Model User's Manual. Geogr. Bernensia, Series P, Vol. 35, Bern

Martinez Beltran J (1978) Drainage and reclamation of salt affected soils in the Bardenas area, Spain. International Institute for Land Reclamation and Improvement, Wageningen

Matthews DA (1989) Programme Al Ghait – Morocco winter snowpack augmentation project. Final report. Department of the Interior, Washington DC

Menking KM, Syed KH, Anderson RY, Shafike NG, Arnold JG (2003) Model estimates of runoff in the closed, semiarid Estancia basin, central New Mexico, USA. Hydrolog Sci J 48(6):953-970

Ministère des travaux publics (ed) (1998) Etude du plan directeur de l'aménagement des eaux des bassins sud-atlasiques, Mission 3: Etude des schemas d'aménagement. Rabat

Ministry of Economy (ed) (1959) Geological Map of Morocco 1:500000, Sheet Ouarzazate. Rabat

Neitsch SL, Arnold JG, Williams JR (1999) Soil and Water Assessment Tool - User Manual. USDA-ARS, Temple, TX

NRCS (ed) (1986) Urban Hydrology for Small Watersheds. USDA, Engineering Division, Technical Release 55 (TR-55). U.S. Government Printing Office, Washington DC

Office Nationale des Irrigations (ed) (1973) Vallée du Drâa – Palmeraie du Fezouata, Forages de reconnaissance et d'études. Résultats de Travaux. Rabat

ORMVAO (Office Régionale de Mise en Valeur Agricole de Ouarzazate) (ed) (1995) Étude d'amélioration de l'exploitation des systèmes d'irrigation et de drainage de l'ORMVAO-Phase 1 – Diagnostic de la situation actuelle, Vol. 1. Ouarzazate

Ouhajou L (1996) Espace hydraulique et société au Maroc – Cas des systèmes d'irrigation dans la vallée du Drâa. Faculté des Lettres et des Sciences Humaines. Thèse et Mémoire. Agadir

Poesen J, Lavee H (1994) Rock fragments in top soils: significance and processes. Catena 23(1-2):1-28

Pitlick J (1994) Relation between peak flow, precipitation and physiography for five mountainous regions in the western USA. J Hydrol 158(3-4):219-240

Radanovic R (1968a) Sols de la palmeraie de Mezguita. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Radanovic R (1968b) Sols de la palmeraie de Ternata. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Radanovic R (1968c) Sols de la palmeraie de Tinzouline. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate

Richardson CW, Wright DA (1984) WGEN: A Model for Generating Daily Weather Variables. ARS-8

Riser J (1988) Le Jbel Sarhro et sa retombée saharienne (Sud-Est Marocain) – Étude Géomorphologique. Notes et Memoires du Service Géologique No. 317. Direction de la Géologie. Rabat

Salomonson VV, Appel I (2004) Estimating fractional snow cover from MODIS using the normalized difference snow index. Remote Sens Environ 89(3):351-360

Salvetti A, Ruf W, Burlando P, Juon U, Lehmann C (2002) Hydrotope-based river flow simulation in a Swiss Alpine Catchment accounting for Topographic, Micro-climatic and Land-use Controls. Integrated Assessment and Decision Support, Proceedings of the First Biennial Meeting of the International Environmental Modelling and Software Society, Volume 1, p. 334-339. June 2002

Sanford W (2002) Recharge and groundwater models: an overview. Hydrogeol J 10:110-120

Schulz O (2006) Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M'Goun, Zentraler Hoher Atlas (Marokko). Doctoral thesis, University of Bonn, Bonn. http://hss.uni-bonn.de/diss-online/math-nat-fak/2007/schulz_oliver/index.htm. Accessed 21 October 2009

Schulz O, Busche H, Benbouziane A (2008) Decadal Precipitation Variances and Reservoir Inflow in the Semi-Arid Upper Drâa basin (South-Eastern Morocco). In: Zereini F, Hoetzl H (eds) Climatic Changes and Water Resources in the Middle East and in North Africa. Springer, Wien

Schulz O, de Jong C (2004) Snowmelt and sublimation: field experiments and modelling in the High Atlas Mountains of Morocco. Hydrol Earth Syst Sc 8(6):1076-1089

Schwarze R (1999) Skalenwechsel über Parameter: Grundwasser. In: Kleeberg H, Mauser W, Peschke G, Streit U (eds) Hydrologie und Regionalisierung. DFG Research Report. Wiley, Weinheim

Sloan PG, Moore ID (1984) Modeling subsurface stormflow on steeply sloping forested watersheds. Water Resour Res 20(12):1815-1822

Tallaksen LM (1995) A review of baseflow recession analysis. J Hydrol 165(1-4):349-370. doi:10.1016/0022-1694(94)02540-R

Tarboton DG, Luce CH (1996) Utah Energy Balance Snow Accumulation and Melt Model (UEB), Computer model technical description and user's guide. Utah Water Research Laboratory and USDA Forest Service Intermountain Research Station. http://www.engineering.usu.edu/cee/faculty/dtarb/snow/snowrep.pdf. Accessed 21 October 2009

UNESCO-UNDP (ed) (1970) Research and training on irrigation with saline water. Technical Report of UNDP Project: Tunisia. Unesco, Paris

Van Hoorn J W (1981) Salt movement, leaching efficiency, and leaching requirement. Agr Water Manage 4(4):409-428

Viviroli D, Weingartner R, Messerli B (2003) Assessing the hydrological significance of the world's mountains. Mt Res Dev 23(1):32-40

World Bank (ed) (1994): Kingdom of Morocco. A water sector review. Unpublished

Youbi L (1990) Hydrologie du Bassin du Dadès. Ministere de l'Agriculture et de la Reforme Agraire, Office Regional de Mise en Valeur Agricole de Ouarzazate. Ouarzazate

van Wesemael B, Mulligan M, Poesen J (2000) Spatial patterns of soil water balance on intensively cultivated hillslopes in a semi-arid environment: the impact of rock fragments and soil thickness. Hydrol Process 14 :1811-1828

Weber B (2004) Untersuchungen zum Bodenwasserhaushalt und Modellierung der Bodenwasserflüsse entlang eines Höhen- und Ariditätsgradienten (SE Marokko). Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/weber_benedikt/index.htm.
Accessed 21 October 2009

Williams JR (1969) Flood routing with variable travel time or variable storage co-efficients. Trans ASAE 12(1):100-103

Zivcovic B (1968) Sols de la palmeraie de M'Hamid. Amenagement de la Vallée du Drâa. Ministère du l'Agriculture et de la Reforme Agraire. ORMVAO, Ouarzazate





7 Biosphere

7.1 Vegetation cover and land use change in Benin

7.1.1 Introduction

7.1.2 Characterizing vegetation cover in Benin using NDVI calculations from remote sensing data

7.1.3 Fire: Some quantifications of this important ecological factor of savannas

7.1.4 Assessing natural vegetation and land use distribution in Central Benin

7.1.5 Changing land use: Hot spots of current land use and land cover changes

7.1.6 Conclusions

7.2 Vegetation dynamics under climate stress and land use pressure in the Drâa catchment

7.2.1 Introduction

7.2.2 Vegetation units

7.2.3 Plant diversity along gradients

7.2.4 Resilience of arid and semi-arid ecosystems

7.2.5 Rehabilitation pace

7.2.6 Conclusions

I-7 Biosphere

J. Röhrig and H. Goldbach

Vegetation and vegetation dynamics strongly impact global and regional water cycles affecting both, climate (see chap. I-5) and water availability (see chap. I-6). Furthermore, land cover and land use have a significant impact on the sustainability of resource management and socio-economic factors such as food and income production and human migration. The actual vegetation cover in Benin and Morocco is very diverse (described in detail in sect. I-3.6). Vegetation dynamics are caused by seasonal climate changes, altered soil properties, human land management which is driven *inter aliae* by economic factors. In addition to seasonal vegetation dynamics, in both study areas the expansion of land use has modified or even eliminated natural vegetation causing land degradation in several regions. Particularly in the Drâa catchment in Morocco, extensive grazing, irrigation with subsequent salinization as well as firewood collection have degraded vegetation cover and plant diversity. In Benin, human activities have altered the current species composition of savannas and have negatively impacted forest regions. In Central Benin, increased agricultural activities and bush fire frequency have significantly changed the vegetation cover within recent years.

This chapter discusses the primary factors influencing vegetation dynamics and land use change in the two research areas in Benin and Morocco. In section I-7.1 vegetation cover and dynamics in Benin are analyzed by remote sensing. We first present the spatial distribution of vegetation cover in Benin as shown through low resolution data (NOAA NDVI; Normalized Difference Vegetation Index). We then consider the spatial and temporal distribution of bush fire using MODIS data at a moderate resolution. Finally, land cover and land use dynamics in Central Benin are presented in greater detail with LANDSAT images. In section I-7.2, the impact of topographic gradients on plant diversity and life forms is analyzed for the Drâa catchment in Morocco based on own field surveys. We further discuss the reaction of different vegetation units to climatic fluctuations and land use pressure, integrating concepts of resilience and rehabilitation.

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I-7.1 Vegetation cover and land use change in Benin

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Abstract

Land surface parameters are important factors of the socio-ecological system. In central Benin the land cover is subject to strong changes, either due to seasonal dynamics or due to rapid land use changes.

To assess land cover performance and calculate the land cover types as well as their transformation, different satellite remote sensing data sets are used covering all of Benin with low spatial resolution and the Upper Ouémé catchment with high resolution. Time series of the low resolution data show the high intra-annual changes of the vegetation cover due to seasonal bush fires. Up to 23% of the total area of Benin is affected by one or more fire events between 2000 and 2009.

The high population growth rates are one of the reasons of the rapid land cover and land use changes especially in Central Benin. The majority of the people is working in the agricultural sector or depends on it. Analyses based on high resolution LANDSAT data reveal that the agricultural area increased by up to 55% in the period from 1991 to 2000. Those land use changes are unevenly distributed in space and hot spots are identified. The loss of savannas and forests is detected by NDVI time series analyses of low resolution satellite data. The results of these satellite-based analyses form the basis for hydrological and land-use modeling as well as soil erosion assessment in the study area.

Keywords: Vegetation trends, NDVI, bush fire, burned area, remote sensing, land cover, land use, classification, change detection

I-7.1.1 Introduction

Vegetation cover and land use are key parameters in the hydrological cycle and are important for the socio-economic conditions including food security, agricultural colonization, and human migration. In Benin, particularly in the central part, recent years have witnessed changes in land use and land cover due to population expansion and economic development (see sect. I-3.8; Adjanohoun et al. 1989; CENATEL 2002; Igué et al. 2004). Primary vegetation has remained only within forests protected by the state or religious convictions and in marginal areas

such as inselbergs and sites with ironstone (Bohlinger 1998; Reiff 1998; Neumann et al. 2004). Additionally, species composition of the savannas all over the country has been altered primarily by human activities (Bohlinger 1998; Neumann et al. 2004; Orthmann 2005). To define projections of future land use and land cover (see sect. II-4.3), it is essential to produce concrete information regarding recent changes and trends in land use. This information can be used to construct sustainable resource management policies. We used remote sensing techniques and satellite data from different sources to determine the current vegetation cover and to assess ongoing changes. The spatial patterns of vegetation cover and trends were derived using low resolution data (NOAA AVHRR) for the whole of Benin (see subsect. I-7.1.2). Bush fire is a common event in the savanna ecosystem and is widely initiated during different land use purposes. A first assessment of the spatio-temporal dynamics in Benin was made using MODIS remote sensing data and was complemented by field surveys (see subsect. I-7.1.3). In addition, land cover and land use dynamics were investigated in more detail for the IMPETUS study area, the Upper Ouémé catchment in Central Benin (see subsect. I-7.1.4).

I-7.1.2 Characterizing vegetation cover in Benin using NDVI calculations from remote sensing data

Remote sensing is commonly used to gain information about the actual vegetation cover and its characteristics and trends of both. Monitoring approaches are frequently based on land cover performance through vegetation indices including the NDVI (Normalized Difference Vegetation Index; e.g., Tucker 1979; Budde et al. 2004; Pettorelli et al. 2005), SAVI (Soil-Adjusted Vegetation Index; Huete 1988), or EVI (Enhanced Vegetation Index; Huete et al. 2002). These indices are based on characteristics of green vegetation: High near infra-red (NIR) and low visible red reflectance (RED) values. The NDVI measures the degree of greenness and quantitatively reflects the capacity of the land to support photosynthesis and primary production.

$$NDVI = (NIR-RED)/(NIR+RED) \qquad \text{(eq. I-7.1.1)}$$

The annual integral of NDVI (integrated NDVI; iNDVI) is an indicator of general land performance over time periods. The value of iNDVI is also strongly correlated with net primary production (NPP e.g., Prince et al. 1998; Li et al. 2004). In Benin we determined the maximum iNDVI between 1982 and 2003 to derive information about the recent spatial distribution of biomass. Therefore, the NDVI 10-day composites from the NOAA Global Inventory Monitoring and Modelling Studies (GIMMS) were taken (Pinzon et al. 2004; Tucker et al. 2005). These data are available online at a resolution of 8 km x 8 km. For western Africa, the more recent and spatially more detailed 1 km SPOT VEGETATION NDVI data is less appropriate than the AVHRR data due to insufficient cloud screening of SPOT

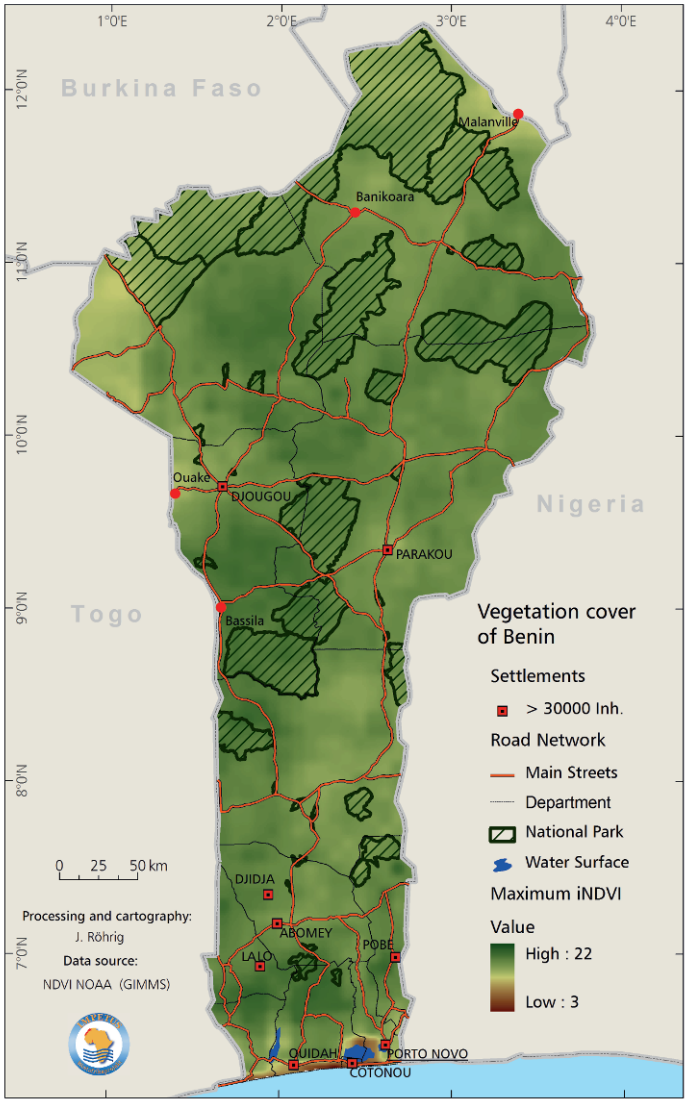

Fig. I-7.1.1: Vegetation cover of Benin assessed with NOAA NDVI data.

suppressing the rainy seasons (see Röhrig et al. 2005; Klein and Röhrig 2006; Fenshold et al. 2007). Figure I-7.1.1 illustrates the iNDVI pattern in Benin. This distribution reflects well the actual patterns of land cover. Higher values indicate a denser and more healthy vegetation cover. Large-area cultivation such as the area nearby Parakou, Djougou, or Banikoara (see subsect. I-7.1.4) are clearly detectable and show lower iNDVI values than the surrounding areas. In contrast, regions with high natural vegetation cover, including the region of Bassila are char-

acterized by higher values. Additionally, degraded sites, like Ouakè in the northwest or Malanville in the north are characterized by low values.

In addition to the vegetation cover over the period 1982-2003, the overall iNDVI trend was assessed for the 22-year period. Long-term decline of vegetation function and productivity serve often as a proxy assessment of land degradation. Figure I-7.1.2 illustrates that several known changes in land use and land cover are detectable with this method, including the widespread transformation of forests into settlements and fields along a new road in the Ouémé catchment built in 1997 (see subsect. I-7.1.4). Certain areas with periodic bush fires, including the protected forests in Central Benin (see fig. I-7.1.3) show clear negative trends. The positive trends seen particularly in the northwestern region may be caused by increased rainfall in this time period and rather small land use changes.

I-7.1.3 Fire: Some quantifications of this important ecological factor of savannas

Large areas of Benin are affected by annual bush fires, raising several concerns. Many factors determine the prevalence of fire, but the current climatic and vegetation conditions make the occurrence of fire very likely. The tropical savanna is characterized by two distinct seasons (see sect. I-3.4). The rainy season determines vegetation growth, which provides fuel. During the dry season, vegetation becomes dry and susceptible to burning. In addition to this pattern of climate, there are other driving factors of bush fire in these areas. Anthropogenic factors are frequently cited, resulting from either intentional or negligent human actions. Recent developments in remote sensing bush fires enable us to systematically study fire distribution and fire regimes on different spatial scales. This subsection investigates bush fire dynamics from 2000 to 2009 using MODIS "Burned Area Products" (MCD45A1) and the results of field surveys performed by local fire management institutions. MODIS burned area level 3 product is derived from processing of combined MODIS-TERRA and MODIS-AQUA 500 m daily land surface reflectance data using a directional reflectance (BRDF) model-based change detection approach (Roy et al. 2005). This algorithm reveals the dates of burning by identifying rapid changes in daily MODIS reflectance time series.

Fire regime in Benin

Bush fires generally occur during the dry season between November and May. In Benin, every year 13% to 23% of the country's territory is burned (see table I-7.1.1). Nearly the entire area of Pendjari National Park burns annually. Generally, an area burns once a year during the dry season, although some regions burn multiple times. Areas that burn several times are usually found inside national parks

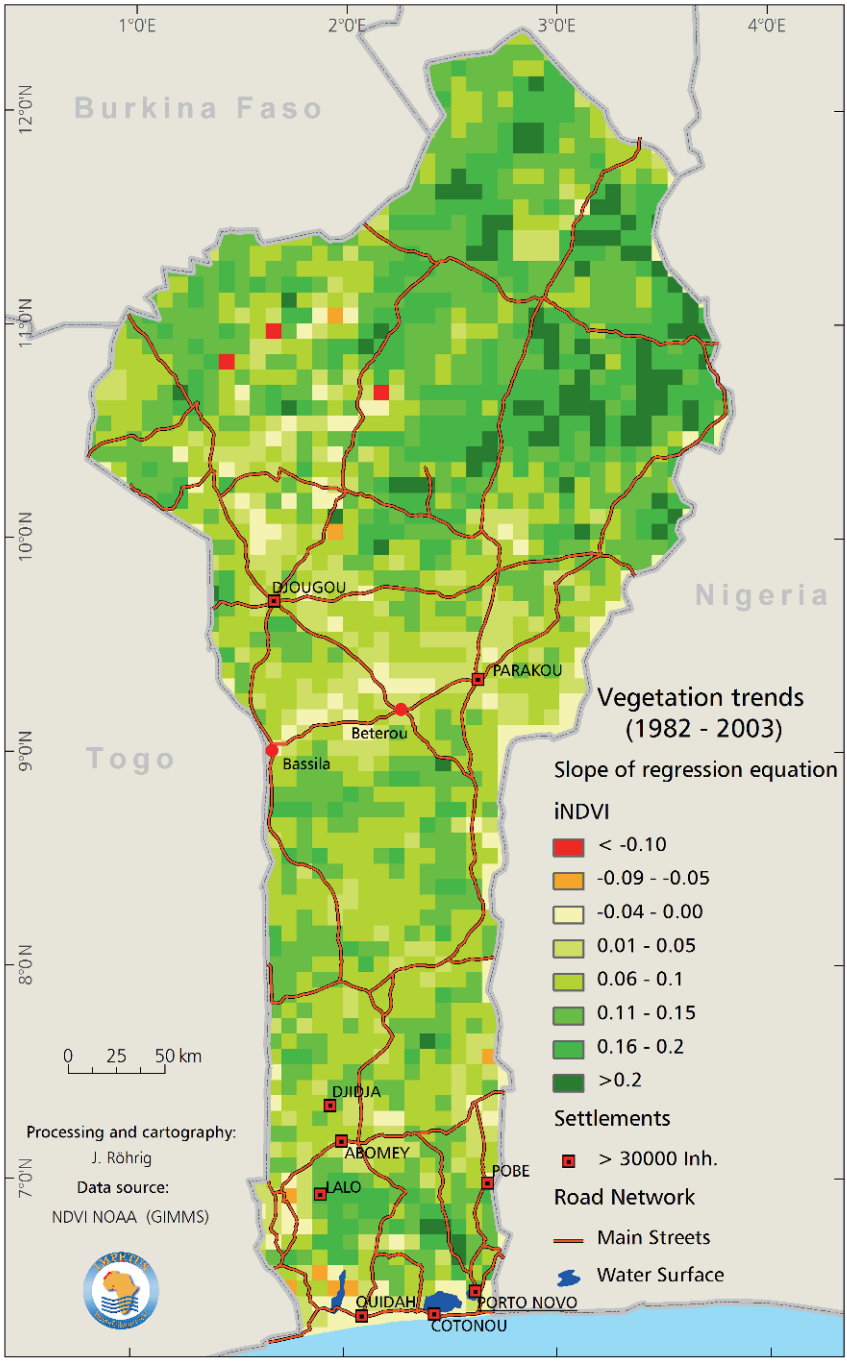

Fig. I-7.1.2: Vegetation trends between 1982 and 2003.

and occur often at the periphery of the late burning sites. These areas are extensions of the late burning areas to the early burned areas (see figs. I-7.1.3 and I-7.1.4). Since 2007, the total area burned and the frequency of fire events decreased each year (see table I-7.1.1).

Bush fire drivers

Clearing natural vegetation with fire to prepare land for agricultural use is a common practice in Benin (FAO 2007). This procedure is a component of the slash-and-burn system used by many farmers. It is not perceived as a disturbance by farmers and is regarded as necessary in clearing new agricultural areas. According to farmers, ashes from the burned plant biomass improve soil fertility, which is required for yam cultivation in the central and northern parts of the country. This method is also a way to fight plant pests. Agricultural land clearing fires occur between February and April late in the dry season and continue until the first rains occur (for the southern zone with bimodal rainfall) (see figs. I-7.1.3 and I-7.1.4) or until May (for the Sudanian and Sudano-Sahelian region). Hunting occurs during the dry season and frequently results in bush fires which burn out of control and cause extensive property damage and mortalities each year. Fires for hunting are used in Central and northern Benin. Small hunting fires are lit early in the dry

Table I-7.1.1: Evolution in pixel count of fire frequency from 2000 to 2009 based on MODIS Fire Product (one pixel: 500m x 500m).

Frequency	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009
0	433,382	434,645	420,468	452,593	458,937	437,786	437,355	468,705	475,433
1	109,865	108,381	122,312	90,709	84,935	104,915	105,666	74,711	68,024
2	1,525	1,745	1,938	1,452	901	2,044	1,738	1,346	1,313
3	3	4	56	21	2	29	16	13	5
4	0	0	1	0	0	1	0	0	0
burned pixel (total)	111,393	110,130	124,307	92,182	85,838	106,989	107,420	76,070	69,342
proportion of burned area [%]	20	20	23	17	16	20	20	14	13

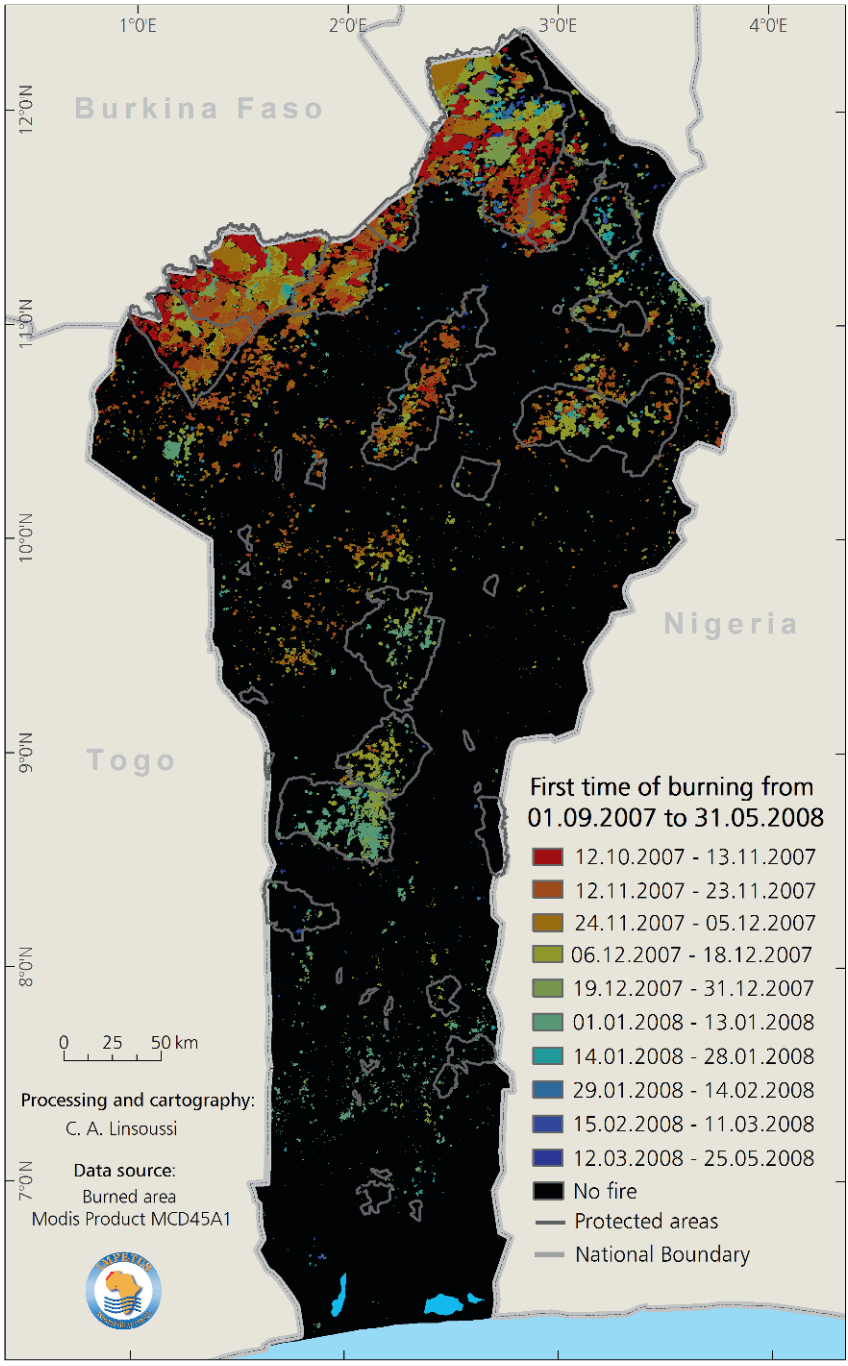

Fig. I-7.1.3: First time of burning from 01.09.2007 to 31.05.2008.

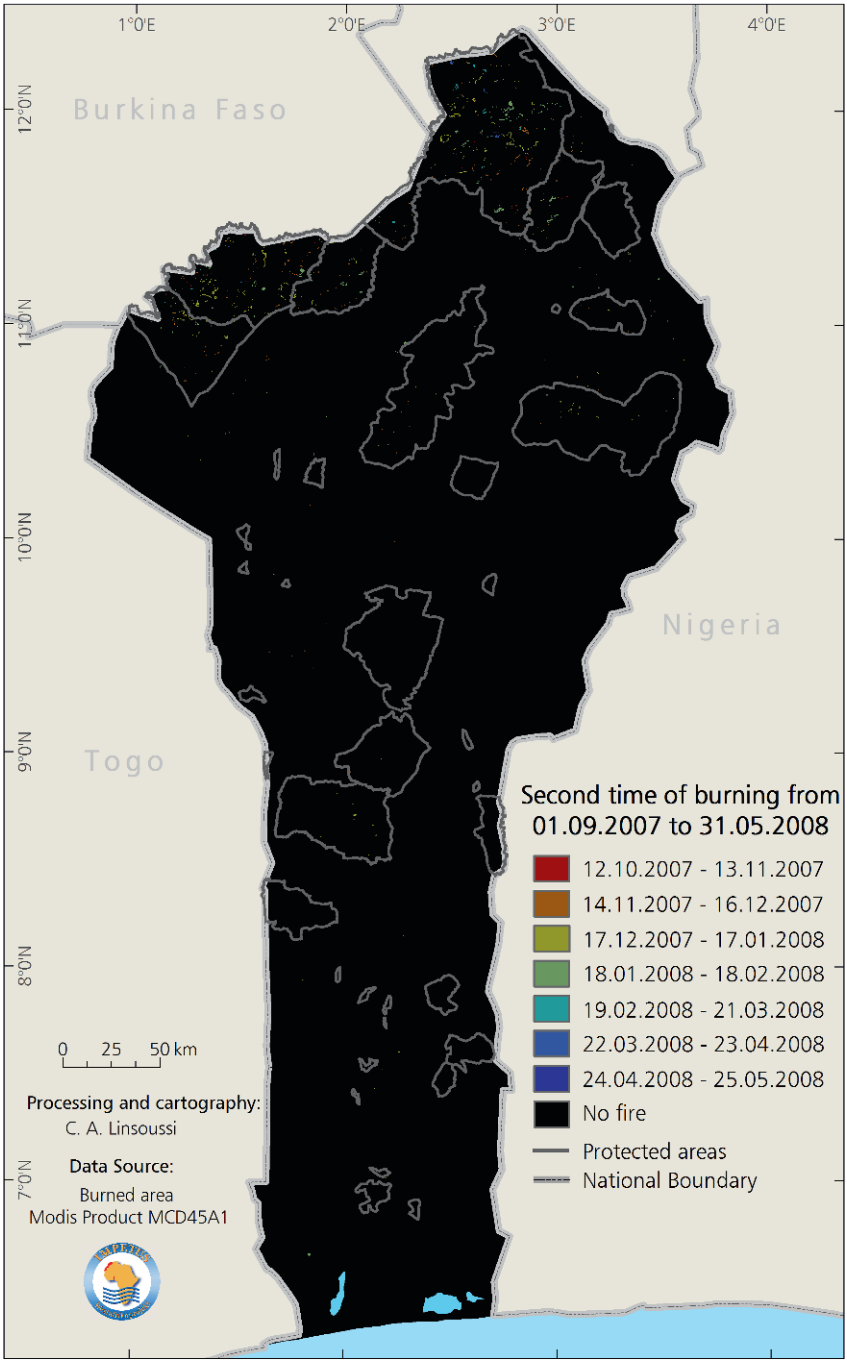

Fig. I-7.1.4: Second time of burning from 01.09.2007 to 31.05.2008.

season in December by small groups of young men hunting small animals such as rodents. The larger fires occur later in the season and are often organized in each village or group of villages during the dry season from January to May (DGFRN 2008). This type of fire is most widespread because it is organised by large groups of people using great transportation means. Gathering wild honey in the forests and savannas is another important activity during the dry season. Fire torches are used at night to destroy bee hives, and are often abandoned in the vegetation and generate uncontrolled bush fires (DGFRN 2008). Fires for pastoral use occur mainly in the dry season, affecting the entire country. These fires are started by shepherds on transhumance to stimulate the natural regeneration of fresh forage. These pastoral fires are uncontrolled and are sometimes the source of conflict with local farmers. They are the likely primary cause of burning of protected areas (*forêt classée*). Large areas of savannahs, forests, and fallows are affected every dry season by these fires. In addition, protective fires are lit ubiquitously very early in the dry season. These are used to clear flammable vegetation that could become fuel for accidental fire. Many infrastructures including houses and lofts are protected in this manner. This method is also used to burn areas around private plantations of palm, teak, and fruit orchards. Fire is used by rural individuals to stimulate the renewal of *Vitex doniana* leaves, which are sold in local markets as vegetable. During the dry season, women set fire to fallow land and later harvest young leaves from the burned areas. This type of fire is primarily used in the regions of Atlantique and Zou and can affect large areas. Burnings are controlled by forest officers in charge of managing protected areas and state-owned plantations. At national parks Pendjari and W in the North, fire is used as a planning tool for protection, forage production (pasture regeneration) and facilitating sightseeing for tourists.

The legislation in Benin allows only controlled fires in the vegetation and bans uncontrolled fires. Every year the government officially defines the periods of the fire season within each region. Unfortunately, there are no appropriate means to monitor and assess compliance with these official periods.

I-7.1.4 Assessing natural vegetation and land use distribution in Central Benin

Remote sensing data collected by satellites are routinely employed in land use and land cover analyses, particularly in remote areas where no or limited information is available. Because little land cover information is available in most parts of Benin, satellite image analysis represents an excellent method to characterize spatio-temporal characterization of land cover and land use (Jensen 1996; Richards and Jia 2006). This method allows obtaining very high spatial homogeneity and high resolution results.

Data and methods

Multi-temporal, high resolution optical LANDSAT TM and ETM+ data were used to map land use and detect changes in land use. Gaps in the LANDSAT data set due to clouds or bush fire smoke were filled using ASTER images. In total, two LANDSAT TM scenes were used; seven LANDSAT ETM+ scenes and two ASTER scenes. One LANDSAT scene covers 180 km x 180 km at a nominal pixel resolution at nadir of 30 m × 30 m (Irish 2000). The multi-spectral ASTER sensor covers with the first five channels the same spectral range as LANDSAT channels 2, 5, and 7. A single ASTER image nominally covers a 60 km × 60 km scene at a spatial resolution of 15 m × 15 m (ERSDAC 2005). To analyze the land use and land cover changes in the Upper Ouémé catchment a complete set of data of the years 1991 and 2000 were used.

All scenes were geometrically corrected and standardized to a set of scenes with very high precision by image-to-image co-registration. Atmospheric correction was not applied as each dataset was classified separately due to seasonal changes (Song et al. 2001). Only LANDSAT scenes from the same recording time and of the same path were tiled and analyzed simultaneously.

To gain information about land cover and land use, the multi-spectral satellite images were transformed into land cover and land use classes through a classification algorithm. The maximum-likelihood classifier (MLC) (see Richards and Jia 2006) was selected for the generation of the land use and land cover maps for 1991 and 2000. For the classification of 1991 LANDSAT imagery, the training data were collected directly from the satellite data through image interpretation because no ground truth data were available. For the 2000 LANDSAT data, 170 training data points from ground truth was used for classification as well as over 300 validation points (Judex 2008c).

Table I-7.1.2: Used datasets for land cover and land use analysis.

Sensor	Recording time	Path / Row	Gap fill
LANDSAT TM	13.12.1991	192 / 53+54	
LANDSAT TM	10.01.1991	193 / 53	
LANDSAT ETM+	26.10.2000	192 / 53+54	
LANDSAT ETM+	13.12.2000	192 / 54	X
LANDSAT ETM+	04.12.2000	193 / 53	
LANDSAT ETM+	07.12.2001	193 / 53	X
LANDSAT ETM+	29.10.2001	192 / 54	X
LANDSAT ETM+	16.12.2001	192 / 54	X
LANDSAT ETM+	03.12.2002	192 / 54	X
ASTER	13.12.2000	(192 / 54)	X
ASTER	19.10.2003	(192 / 54)	X

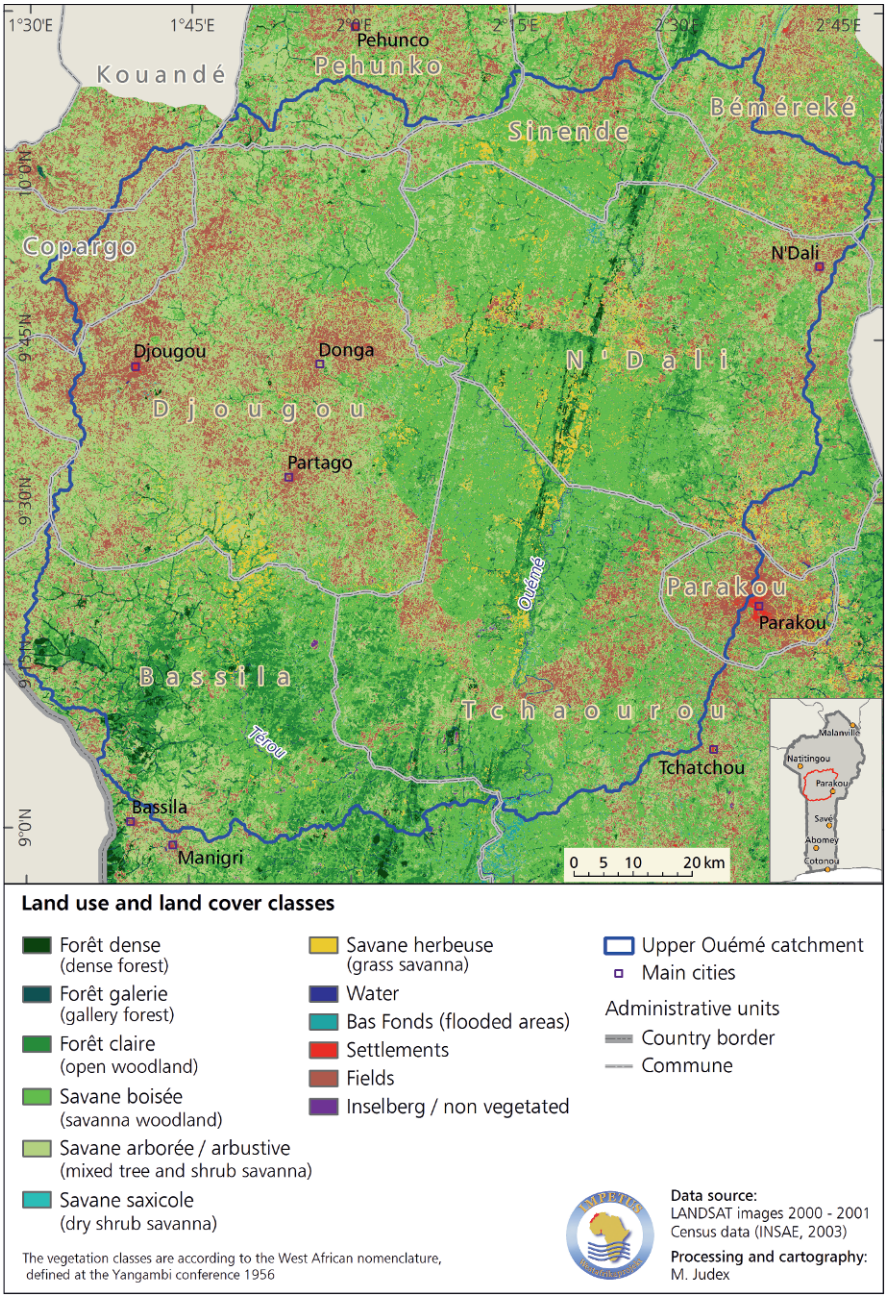

Fig. I-7.1.5: Map of land use and land cover of Central Benin in 2000 (Source: Judex et al. 2008a).

We employed a classification scheme adapted and extended from Reiff (1998), consisting of three principal categories: Type I - natural vegetation and fallow vegetation, type II - intensively used areas, and type III - water surfaces. Altogether 13 classes were defined (including a class "burned area" for the 1991 data; see fig. I-7.1.5. Previous work has shown that for very small field sizes (mean field size < 0.3 ha) accurate identification and classification of different crops is not possible (Judex 2003). In addition, a multi-spectral classification approach alone did not result in a land use and land cover map of sufficient accuracy for these purposes. Therefore, spectral classification techniques were extended by employing a 'knowledge-based' approach, which included information about the landscape (i.e. knowledge about the location of each pixel in the landscape; see Judex et al. 2006). Land use changes were then assessed using a post-classification comparison method.

Satellite image classification

The high resolution land use and land cover map from the year 2000 is shown in figure I-7.1.5. Most of the areas in Central Benin are covered with semi-natural vegetation (87.8%). Only 12% are currently used as field areas. However, a large fraction of the savannah vegetation belongs to the short to long term rotational fallow cycle, the local mechanism to maintain soil fertility (see sect. I-3.10). Calculation of exact values is not possible because of the similarity in reflectance of fallow and natural vegetation. The distribution of all land use and land cover classes is shown in figure I-7.1.5 which indicates the high fraction of savannah vegetation types in the study area.

The distribution of land use is very unequal in space. Due to higher population densities, the regions around Djougou and Parakou are used intensively. Only very few small forest areas remain, mainly holy forests (*forêts sacrées*). The highest proportion of undisturbed areas is located inside protected zones, the so called *forêts classées*, e.g. the *forêts classées de l'Ouémé superieure* visible in the middle part in figure I-7.1.5. Unprotected areas with large undisturbed forests and savannahs exist in Central Benin, serving as an incentive to many land searching farmers from the northern part of the country (see next subsection). Table I-7.1.3 lists the shares of aggregated land cover and land use categories for the main municipalities (*communes*) in Central Benin. Djougou features the highest population density, with 46.1 inhab./km², and has the highest proportion of agricultural land use with nearly 22% of the total surface in use. More than 50% of the area is occupied by savanna which can be assumed to be fallow vegetation. The situation in the commune Bassila is very different, with a large proportion of forest area and very little agricultural land use. N'Dali and Tchaourou have also high proportions of forest areas but slightly more agricultural areas than Bassila.

Table I-7.1.3: Surface percentages of important land cover categories for four communes in Central Benin (in 2000).

Commune	Forest[1]	Savannah[2]	Agriculture
Djougou	20.1%	50.9%	21.8%
Bassila	72.0%	23.0%	4.8%
N'Dali	56.2%	34.3%	9.3%
Tchaourou	62.2%	26.0%	10.4%

[1] Forest = *forêt dense, forêt claire, savane boisée*;
[2] Savannah = *savane arborée / arbustive, savane saxicole*

I-7.1.5 Changing land use: Hot spots of current land use and land cover changes

Analyzing detailed spatial land use and land cover changes is possible with multi-temporal remote sensing data. We compared data from 1991 and 2000 by a pixel-by-pixel based change detection method. The result is a) a contingency matrix in which changes for every land use / land cover combination are quantified and b) maps identifying locations of changes at the pixel level.

High intra-annual vegetation dynamics pose a problem in detecting and analyzing changes in this area. Data from 1991 were taken during the dry season when a considerable amount of area was affected by bush fire; burned area was less prevalent during 2000. Therefore, the interpretation of some class combinations seems to be not plausible at first glance in table I-7.1.4.

Most of the changes are attributable to seasonal changes: 35% of the total area is affected by bush fires causing changes in several vegetation classes. However, land cover changes due to anthropogenic deforestation and agricultural expansion are also clear. During the observation period, the agricultural areas increased by 45% in the Upper Ouémé catchment. Our analyses further revealed the spatial distribution of 'hot spots' of that change (see fig. I-7.1.6). These areas correspond to regions of high population growth and considerable land resource availability. Many change hot spots are located in the neighborhood of large protected forest areas or are near large cities (e.g., Parakou). The deforestation hot spots are shown in figure I-7.1.6. These changes in land use pose a major threat to remaining forest resources.

The observed land use and land cover changes are likely to continue because there is no regional land use planning or regulating activities, and agricultural production capacities are projected to remain low. Therefore, livelihood security may be threatened due to decreasing land availability and declining soil fertility (see sect. II-4.1).

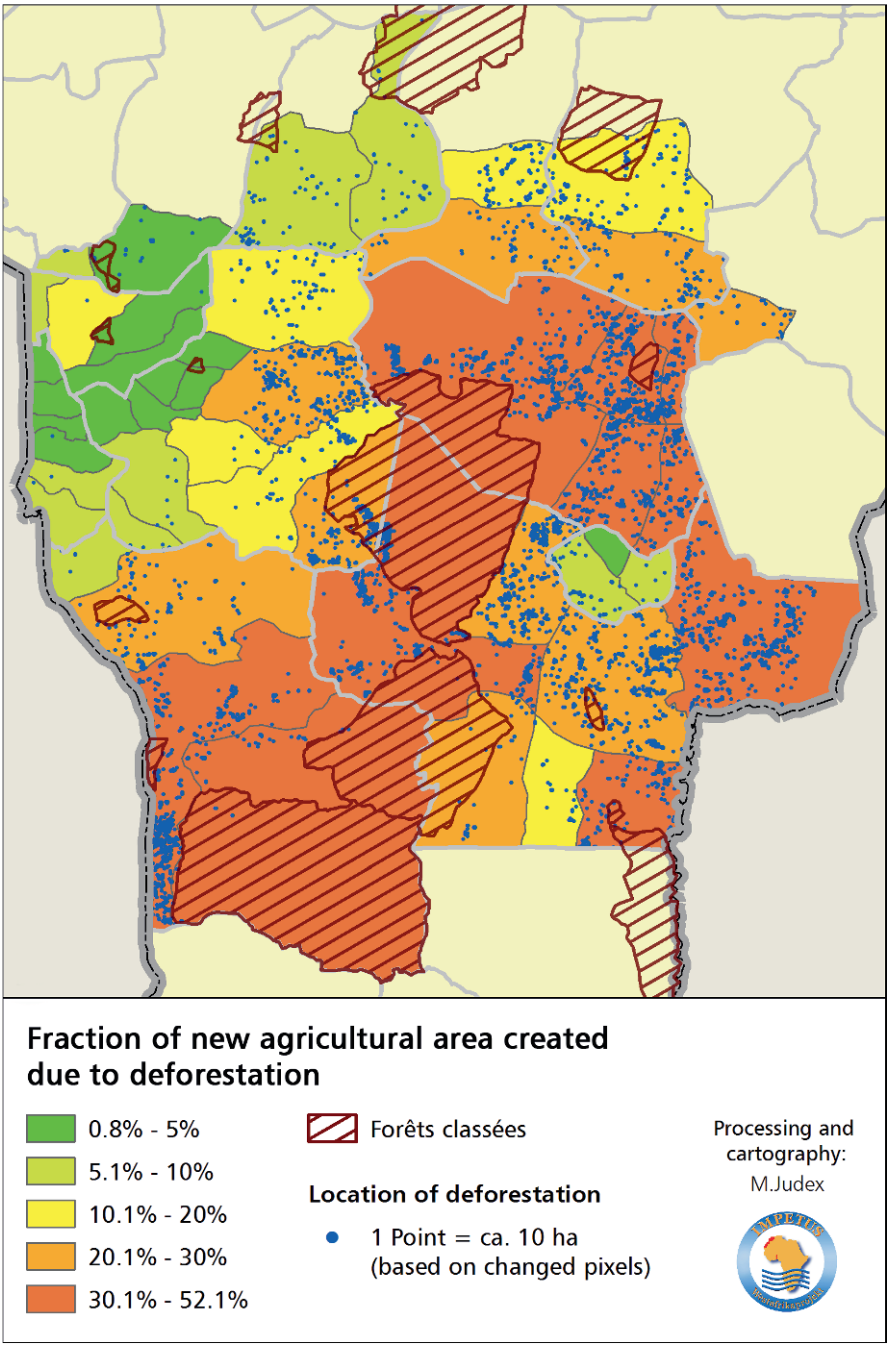

Fig. I-7.1.6: Land cover and land use changes due to deforestation in Central Benin. Data derived from LANDSAT images (13.12.1991 and 26.10.2000) (Source: Judex et al. 2008b).

Table I-7.1.4: Results of land use classifications of 1991 and 2000 [in hectares] and changes [in percent] for four communes in Central Benin.

		Forest & dense savannah	Savannah	Settlement	Agricultural area	Burned area
Tchaourou	1991	351,219	54,965	139	38,838	208,603
	2000	431,782	159,293	424	60,452	0
	change	22.9%	189.8%	205.0%	55.7%	-100.0%
N'Dali	1991	221,881	37,391	106	24,046	92,595
	2000	225,521	119,470	289	30,363	0
	change	1.6%	219.5%	172.6%	26.3%	-100.0%
Bassila	1991	377,605	23,213	68	16,843	154,793
	2000	431,917	116,089	135	23,918	0
	change	14.4%	400.1%	98.5%	42.0%	-100.0%
Djougou	1991	100,955	71,270	237	47,706	173,403
	2000	99,625	213,653	672	79,483	0
	change	-1.3%	199.8%	183.5%	66.6%	-100.0%

I-7.1.6 Conclusions

Analysis of remote sensing data clearly shows the spatio-temporal dynamics of vegetation cover and land use in Benin. Two primary factors determine the vegetation cover in Benin: the strong seasonal dynamics which are the prerequisite for the bush fires and the extremely high rate of land cover change. Although laws regulate bush fire, traditional burning procedures are still practiced. The high rate of population growth is one of the main drivers of land use and land cover changes. Considerable changes are apparent even at coarse resolution across Benin whereas with high resolution data detailed change directions were calculated. Although large forest areas are still present, particularly in the central part of Benin, population pressure is already noticeable as people migrate into these regions. If population density rises, resource planning becomes increasingly necessary to prevent conflicts and to maintain ecosystem services.

References

Adjanohoun EJ, Adjakidje V, Ahyi MRA, Aké assi L, Akoegninou A, d'Almeida J, Apovo F, Boukef K, Chadare M, Cusset G, Dramane K, Eyme J, Gassita J-N, Gbaguidi N, Goudote E, Guinko P, Houngnon, P, Lo I, Keita A, Kiniffo HV, Kone-Bamba D, Musampa Nseyya A, Saadou M, Sodogandji Th, de Souza S, Tchabi A, Zinsou Dossa C, Zohoun Th (1989) Contribution aux études ethnobotaniques et floristiques en République Populaire du Bénin. Médecine traditionnelle et pharmacopée. Agence de Coopération Culturelle et Technique, Paris

Bohlinger B (1998) Die Spontane Vegetation in traditionellen Anbausystemen Benins: Ihre Bedeutung und Möglichkeiten des Managements. PLITS 16 (1). University of Hohenheim, Stuttgart

Budde ME, Tappan G, Rowland J, Lewis J, Tieszen LL (2004) Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI and local variance analysis. J Arid Environ 59(3):481-498

CENATEL (2002) Rapport final: Base de données georeferencées sur l'utilisation agricole des terres au Bénin. Contrat N° 23428. Cotonou

DGFRN (2008) Diagnostic participatif des feux de brousse au Benin & stratégie nationale de gestion des feux de végétation. Internal report. Cotonou

ERSDAC (2005) ASTER User's Guide. Part I. General (V 4.0). Earth Remote Sensing Data Analysis Center – technical report

FAO (2007) Fire management global assessment 2006. Rome

Fenshold R, Nielsen TT, Stisen S (2007) Evaluation of AVHRR PAL and GIMMS 10-day composite NDVI time series product using SPOT-4 vegetation data for the African continent. Int J Remote Sens 27(13):2719-2733

Huete AR (1988) A soil-adjusted vegetation index (SAVI). Remote Sens Environ 25:295-309

Huete A, Didan K, Miura T, Rodriguez E (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens Environ 83:195-213

Igué AM, Gaiser T, Stahr K (2004) A soil and terrain digital database for improved land use planning in Central Benin. Eur J Agron 21:41-52

Irish R (2000) Landsat 7 Science Data User Handbook. http://landsathandbook.gsfc.nasa.gov/handbook.html. Accessed 28 November 2009

Jensen J (1996) Introductory digital image processing. A remote sensing perspective. 2nd edn. Prentice Hall, New Jersey

Judex M (2003) Analyse und Erklärung der Landbedeckungs- und Landnutzungsänderungen im Upper Oueme Catchment (Benin, Westafrika) durch die Verknüpfung von LANDSAT Daten mit sozioökonomischen Daten. Diploma thesis, University of Bonn, Bonn

Judex M, Thamm H-P, Menz G (2006) Improving land-cover classification with a knowledebased approach and ancillay data. In: Braun M (ed) Proceedings of Second Workshop of the EARSeL SIG on Remote Sensing of Land Use & Land Cover: Application & Development, Bonn, 28-30 September 2006

Judex M, Thamm H-P, Menz G (2008a) Land Use and Land Cover in Central Benin. In: Judex M, Thamm, H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 85-86. Department of Geography, University of Bonn, Bonn

Judex M, Thamm H-P, Menz G (2008b) Land Use Dynamics in Central Benin. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 87-88. Department of Geography, University of Bonn, Bonn

Judex M (2008c) Modellierung der Landnutzungsdynamik in Zentralbenin mit dem XULU-Framework. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/judex_michael. Accessed 12 September 2008

Klein D, Röhrig J (2006) How does vegetation respond to rainfall variability in a semi-humid West African in comparison to a semi-arid East African environment? In: Braun M (ed) Proceedings of Second Workshop of the EARSeL SIG on Remote Sensing of Land Use & Land Cover: Application & Development, pp. 149-156. Bonn, 28-30 September 2006

Li J, Lewis J, Rowland J, Tappan G, Tieszen LL (2004) Evaluation of land performance in Senegal using multi-temporal NDVI and rainfall series. J Arid Environ 59(3):463-480

Neumann K, Hahn-Hadjali K, Salzmann U (2004) Die Savanne der Sudanzone in Westafrika: Natürlich oder menschengemacht. In: Albert K-D, Löhr D, Neumann K (eds) Mensch und Natur in Westafrika: Kapitel. 2.1. Ergebnisse aus dem Sonderforschungsbereich 268, Kulturentwicklung und Sprachgeschichte im Naturraum Westafrikanische Savanne, pp. 39-68. DFG. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Orthmann B (2005) Vegetation ecology of a woodland-savanna mosaic in central Benin (West Africa): Ecosystem analysis with a focus on the impact of selective logging. Doctoral thesis, University of Rostock, Rostock

Pettorelli N, Vik JO, Mysterud A, Gaillard JM, Tucker CJ, Stenseth NC (2005) Using the satellite-derived Normalized Difference Vegetation Index (NDVI) to assess ecological effects of environmental change. Trends Ecol Evol 20(9):503-510

Pinzon J, Brown ME, Tucker CJ (2004) Satellite time series correction of orbital drift artifacts using empirical mode decomposition. In: Huang N (ed) Hilbert-Huang Transform: Introduction and Applications. Chapter 10 (II). Applications, pp. 167-186. World Scientific Publishing, London

Prince SD, Goetz S, Czajkowski K, Dubayah R, Goward, SN (1998) Inference of surface and air temperature, atmospheric precipitable water and vapour pressure deficit using AVHRR satellite observations: validation of algorithms. J Hydrol 212+213: 231-250

Reiff K (1998) Geo- und weideökologische Untersuchungen in der subhumiden Savannenzone NW-Benins. In: Meurer M (ed) Das Weidewirtschaftliche Nutzungspotential der Savannen Nordwest-Benins aus floristischer-vegetationskundlicher Sicht. Karlsruher Schriften zur Geographie und Geoökologie 1, pp. 51-86. University of Karlsruhe, Karlsruhe

Richards J, Jia X (2006) Remote sensing digital image analysis: An Introduction, 4th edn. Springer Berlin, Heidelberg, New York

Roy DP, Jin Y, Lewis PE, Justice CO (2005) Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. Remote Sens Environ 97:137-162

Röhrig J, Thamm H-P, Menz G, Porembski S, Orthmann B (2005) A phenological classification approach for the upper Ouémé in Benin, West Africa using SPOT VEGETATION. In: Veroustraete F, Bartholomé E, Verstraeten WW (eds) Proceedings of the Second International SPOT VEGETATION Users Conference. 1998-2004: 6 years of operational activities, pp. 301-306. Ispra

Song C, Woodcock CE, Seto KC, Lenney MP, Macomber SA (2001) Classification and change detection using Landsat TM data: When and how to correct atmospheric effects? Remote Sens Environ 75:230-244

Tucker, CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens Environ 8:127-150

Tucker CJ, Pinzon JE, Brown ME, Slayback D, Pak EW, Mahoney R, Vermote E, El Saleous N (2005) An extended AVHRR 8-km NDVI data set compatible with MODIS and SPOT Vegetation NDVI Data. Int J Remote Sens 26(20):4485-4498

I-7.2 Vegetation dynamics under climate stress and land use pressure in the Drâa catchment

M. Finckh and H. Goldbach

Abstract

The Drâa catchment comprises parts of the Mediterranean, Ibero-Mauretanian and Saharan floristic regions. Rangeland vegetation is dominated by shrublands, steppes, and deserts. Plant species diversity peaks between 1,500 m and 2,500 m altitude, at the boundary between arid and semi-arid bioclimates, and annual plants strongly contribute to this mid-altitudinal peak in species diversity.

The vegetation of arid disequilibrium systems in the Middle Drâa basin is driven primarily by rainfall and generally shows no signs of degradation. Biomass of non-equilibrium steppes is influenced by rainfall, but the resilience against overgrazing is limited and species composition degrades under strong grazing pressure over long time scales. The standing biomass of semi-arid equilibrium systems with reliable annual precipitation do not show strong interannual fluctuations, but these pastoral ecosystems are frequently overstocked and therefore are subject to severe degradation.

Rehabilitation pace in non-equilibrium systems is relatively quick in terms of biomass rehabilitation, although community restoration takes many years. Regeneration processes in oromediterranean equilibrium ecosystems are extremely slow and require many decades. The actual land use pressure overstresses the resilience of these fragile mountain ecosystems.

Keywords: Southern Morocco, High Atlas, diversity gradient, vegetation, life forms, pastoral ecosystems, arid rangelands, vegetation dynamics, resilience, degradation, rehabilitation

I-7.2.1 Introduction

The Drâa basin comprises the transition zone from sub-humid oromediterranean scrublands to arid Saharan deserts. From the catchment divide in the High Atlas southward, vegetation zones are located along a gradient of increasing temperature and decreasing precipitation. This gradient includes an increasing interannual coefficient of variance for precipitation (Knippertz et al. 2003) and a south-

ward shift in seasonality from Mediterranean-type winter rainfall to bimodal rainfall in spring and autumn (Schulz 2008). The IMPETUS project implemented a gradient oriented monitoring transect for vegetation and climate observations in the Drâa basin (for details on locations, plot design, weather stations, and test site environments see section I-4.3). About 93% of the catchments area is used as rangeland by mobile and sedentary pastoralists. Stocks (and thus grazing pressure) have markedly increased in the High Atlas over the last decades (Chiche 2007). Just about 7% of the area is used for irrigation agriculture in the oases along the streams (Schmidt 2003).

In the following subsection, we will discuss the consequences of the biophysical and socio-economic framework for ecosystem resilience against climate stress and land use pressure.

I-7.2.2 Vegetation units

The Upper and Middle Drâa catchment includes parts of three major floristic regions, the Mediterranean, Ibero-Mauretanian, and Saharan region respectively. Beginning with the High Atlas, the vegetation shows a southward sequence of oromediterranean scree and dwarf-shrub vegetation, Ibero-Mauretanian sagebrush-steppes dominated by *Artemisia herba-alba*, Pre-Saharan *Hammada scoparia* -steppes and *Convolvulus trabutianus* -rock-steppes, down to Saharan semi-deserts and deserts with *Acacia raddiana* dominated wadi-vegetation (Quézel and Barbero 1981; Quézel et al. 1994, 1995; Finckh and Poete 2008). Riparian vegetation along watercourses and agricultural systems show the corresponding transition from (Sub-) Mediterranean to Saharan flora and vegetation.

I-7.2.3 Plant diversity along gradients

Vegetation units generally show specific ranges of vascular plant diversity. In the Drâa region, mean species density on rangelands per 100 m² fluctuates widely between less than five species in extreme Saharan or oromediterranean environments and more than 45 in semi-arid steppes. Species density [100 m²] along the gradient of altitude throughout the Drâa basin shows a unimodal hump shaped distribution (see fig. I-7.2.1), rising steadily from 475 m (or less than 50 mm annual precipitation) to a peak at 2,225 m (or 275 mm Pann, respectively) and decreasing again at higher altitudes. Accumulated species richness along the test site transect attains maxima at total annual precipitation of 225 mm, about 50 mm / 250 m below the peak in species density.

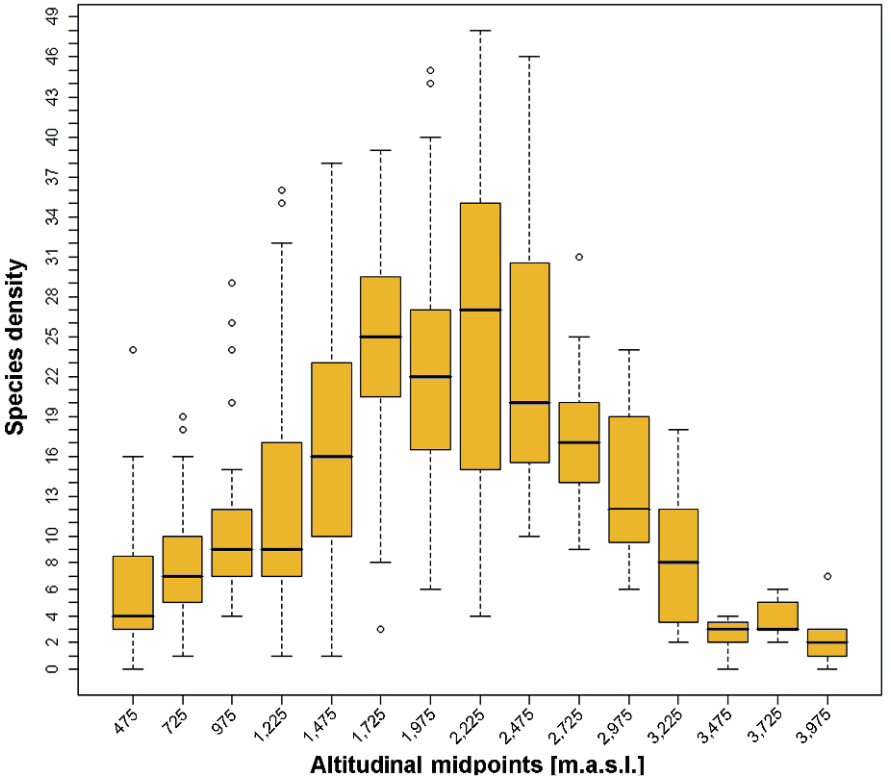

Fig. I-7.2.1: Species densities at 100 m² plots along the altitudinal gradient in the Drâa basin.

There is still no scientific consensus regarding the underlying causes of the hump-shaped functions of alpha diversity along large scale altitudinal gradients (Colwell et al. 2005; Field et al. 2009), although the so-called mid-domain effect (Colwell and Lees 2000) or climate-productivity relationships (Field et al. 2009) are frequently cited to explain such patterns. Limiting environmental factors such as decreasing temperatures at the upper end and decreasing precipitations at the lower end of the altitudinal gradient play a major role for this pattern. The difference between species density and accumulated species richness is due to changes in the life form spectra of the plant communities. Annual species (*thérophytes*) gain prevalence beneath the 200 mm isoline. These species contribute about 60% of the life form spectrum and maintain this threshold at the arid test sites further south (Finckh 2006). As therophyte guilds depend on specific climatic triggers, they can be partly absent in *relevés*. The permanent life forms (*hemicryptophytes, chamaephytes*) that dominate the semi-arid and sub-humid wing of the transect are much more reliable in this respect. Species density is thus closer to total species richness. Apart from this theoretical debate, we observed that species density peaks in the altitudinal belt between 1,500 m and 2,500 m, that the percentage of

small range endemic species increases strongly with altitude (Benabid 2000) and that the heterogeneity of plant communities increases with aridity.

I-7.2.4 Resilience of arid and semi-arid ecosystems

The vegetation units along the transect respond differently to climatic fluctuations. Rank Abundance Distributions are a suitable tool for the analysis of this effect. All species found in one vegetation plot were ranked according to their abundances, i.e. number of individuals. Y-axis shows log-transformed abundances, while the x-axis shows the total number of species found, i.e. species richness. Interannual changes of the curves indicate differences in species and numbers of individuals between years.

Figure I-7.2.2 shows annual rank abundance distributions for a permanent monitoring plot within an exclosure in the arid Jebel Bani chain southwest of Tagounite. We observed few species and individuals present in the first two years after fencing, then a strong increase in both parameters in the relatively wet years 2004 and 2006, followed by a subsequent decrease. A neighboring plot within an exclosure fence showed the same temporal dynamics. We assume that this arid ecosystem

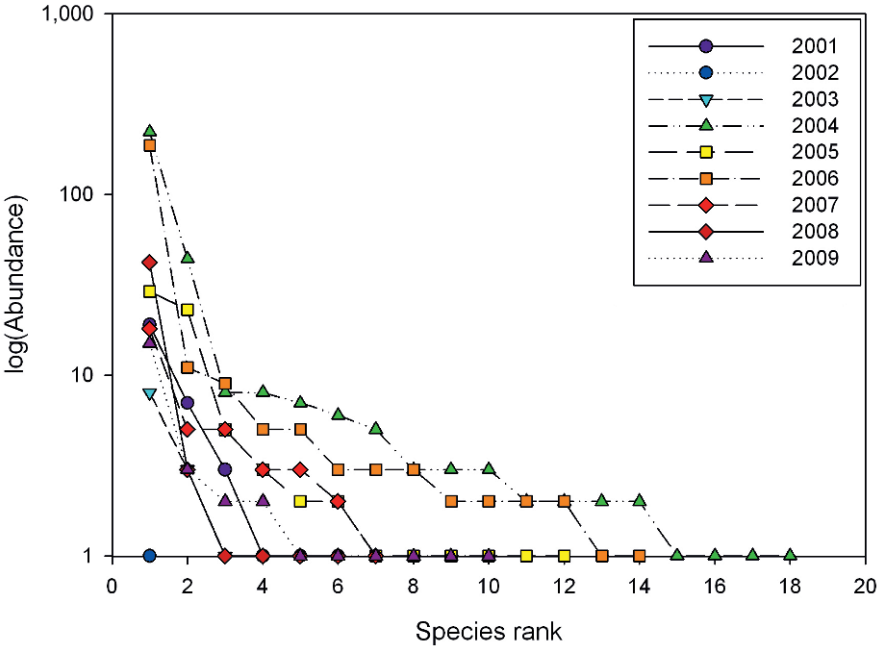

Fig. I-7.2.2: Rank Abundance Distributions for arid ecosystems: the permanent plot JHBZS (sample size: 125 grid cells).

constitutes a disequilibrium system in the strict sense (Gillson and Hoffmann 2007), in which vegetation dynamics are driven primarily by interannual rainfall variability rather than by grazing. If pastoral resources are available, they might be used for grazing, but the strong intra- and interannual fluctuations of biomass do not allow the maintenance of large stocks with permanent and selective grazing pressure.

The vegetation at the test sites receiving between 100 and 200 mm of annual precipitation correspond to nonequilibrium systems in the sense of Gillson and Hoffmann (2007). The standing biomass strongly fluctuates according to the rainfall of the respective season, but the life form spectra are dominated by perennial species. Many of these plants are adapted to strong interannual rainfall variability and able to build up reserves for dry years. If these steppes are subject to long term overgrazing, many species become overstressed and the species composition shifts towards unpalatable and annual species. These systems thus degrade over longer time periods, and productivity becomes less reliable, entering a state of opportunistic reactions to rainfall similar to disequilibrium systems. A few ungrazed vegetation areas remaining in rural cemeteries in the Basin of Ouarzazate and the Jebel Saghro provide evidence of the potential natural vegetation of this steppe belt, which is now almost completely degraded.

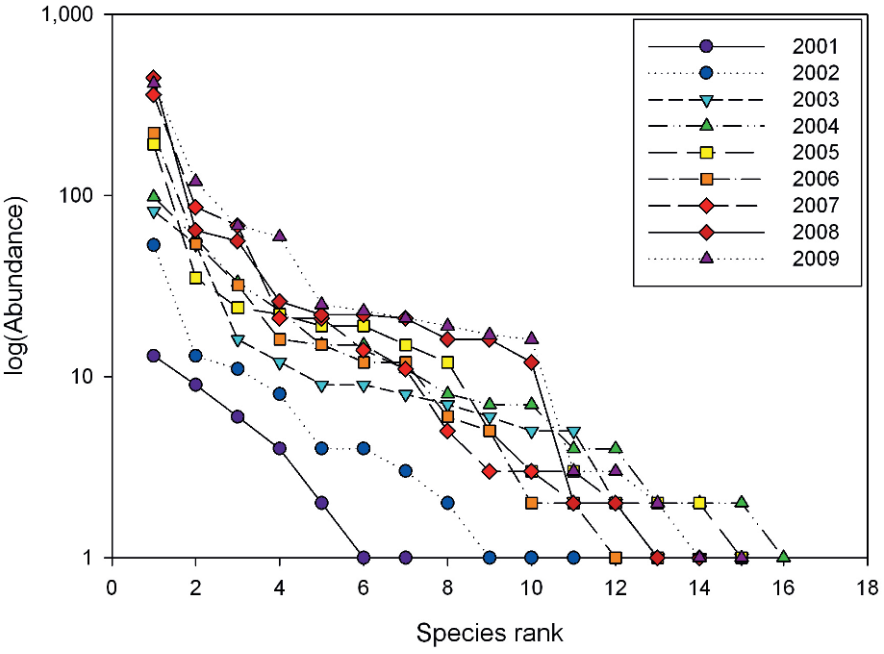

Fig. I-7.2.3: Rank Abundance Distributions for semi-arid mountain ecosystems: the permanent plot TZTZ (sample size: 125 grid cells).

Semi-arid and sub-humid steppes beyond the 200 mm isoline, dominated by perennial shrubs and hemicryptophytes, respond differently to grazing pressure. Rank abundance distributions from the oromediterranean permanent plot TZTZ (see fig. I-7.2.3) do not show strong interannual fluctuations but an increase in species number and abundances was observed during the first two years of fencing. In this equilibrium system with about 500 mm of annual precipitation, rainfall was more consistent, allowing perennial flora to dominate the scrublands (in biomass, not in species number). This permanently available resource facilitates the growth of larger herds present in the region over long periods, leading to a permanent grazing pressure. Rainfall reliability in arid and semi-arid rangelands is a double-edged driver, making the ecosystem subject to unlimited stocking and thus subject to severe degradation over long time periods.

I-7.2.5 Rehabilitation pace

Little is known about the time span necessary for rehabilitation of degraded arid and semi-arid ecosystems. Sagebrush steppes, mainly dominated by short-living dwarf-shrubs and permanent grasses, attain a first regeneration phase within a few



Fig. I-7.2.4: A relict of *Stipa*-dominated grass steppes on a rural cemetery close to Iknioun, Jebel Saghro. The dark brown colours in the background indicate the degraded *Artemisia*-steppes outside of the cemetery.

years, in terms of standing biomass and population structure of the dominating species (unpublished data). However, comparisons to long-term exclosures, e.g., at rural cemeteries, still show key differences in species composition (see fig. I-7.2.4). Recolonization by grazing-sensitive species is a largely stochastic process, dependent on dispersal mechanisms and distances to refuge sites. We still lack data and model approaches required to estimate time spans for complete restoration.

In oromediterranean spiny dwarf-shrub communities' temporal dynamics are much slower. The vegetation period is shorter and growth conditions are more extreme in terms of solar radiation, wind exposure, evaporation, frost, and cryoturbation. At the oromediterranean test sites TIC and TZT in the High Atlas, few species are able to colonize open sites above 3,000 m.

By far the most important pioneer species at open sites is the spiny cushion shrub *Alyssum spinosum*. Once this species is established and has grown up to larger individuals, other species find safe sites for establishment under the tufts. The individuals younger than 30 years represent about 10% of the standing *Alyssum* biomass. The second relevant colonization strategy is clonal growth after establishment at safe sites. This is the case with several grasses, e.g. *Festuca* sp. The surface occupied by this species at test site TZT increased over a five year period only by 10%, so again, this process requires decades to revegetate a degraded site. To summarize, regeneration of vegetation cover in these ecosystems by the primary pioneer species takes decades, and late successionary species grow and establish much slower. The actual grazing pressure and firewood extraction by the local population exceed the growth in biomass and overstress the resilience of these fragile mountain ecosystems. In the long run, this overexploitation has severe consequences for biodiversity, pastoral productivity, slope stability and flash floods.

I-7.2.6 Conclusions

Semiarid to arid steppe ecosystems in southern Morocco differ strongly with regard to vegetation dynamics and resilience. Vegetation dynamics of arid rangelands in the presaharan region are driven mainly by rainfall events and show strong interannual fluctuations. The lack of reliable forage availability hinders the build-up of large stocks of sheep and goats and thus prevents a permanent overstocking. No signs of rangeland degradatation were found in the arid part of the study area.

In contrast to the arid rangelands, biomass in semiarid ibero-mauretanian and oromediterranean rangelands in the southern High Atlas ranges shows minor interannual fluctuations. According to their altitudinal position, they offer reliable grazing resources in spring and autumn (mid altitudes) or in summer (high altitudes). However, the reliability of fodder allows for pastoral land users to build up large stocks with permanent (all year round) presence on the rangelands. In dry years, stocking numbers exceed by far the carrying capacity and resilience of the pastoral

ecosystems and cause the degradation of rangeland vegetation. Important degradation processes comprise decreasing biomass productivity and decreasing vegetation cover which facilitates soil erosion. With regard to floristic changes, palatable and browsing sensitive perennial species disappear and vegetation shifts towards spiny, poisonous or annual species.

Regeneration of natural semiarid rangelands is slow for mid-altitudinal steppes and extremely slow for high altitudinal pastures. Actual land use trends enhance degradation processes and constitute, at least in the medium term, a much stronger driver of desertification than Climate Change.

References

Benabid A (2000) Flore et écosystèmes du Maroc - évaluation et préservation de la biodiversité, 1st edn. Éditions Ibis Press, Paris

Chiche J (2007) History of Mobility and Livestock Production in Morocco. In: Gertel J, Breuer I (eds) Pastoral Morocco - Globalizing Scapes of Mobility and Insecurity, pp. 31-59. Ludwig Reichert Verlag, Wiesbaden

Colwell RK, Lees DC (2000) The mid-domain effect: Geometric constraints on the geography of species richness. Trends Ecol Evol 15:70-76

Colwell RK, Rahbek C, Gotelli NJ (2005) The Mid-Domain Effect: There's a Baby in the Bathwater. Am Nat 166(5), E-reply, E149-E154

Field R, Hawkins BA, Cornell HV, Currie DJ, Diniz-Filho JAF, Guegan J-F, Kaufman DM, Kerr JT, Mittelbach GG, Oberdorff T, O'Brien EM, Turner JRG (2009) Spatial species-richness gradients across scales: A meta-analysis. J Biogeogr 36:132-147

Finckh M (2006) Klima- und Landnutzungs-getriebene Dynamik von Vegetationsmustern in Südmarokko. Ber d Reinh Tüxen-Ges 18:83-99

Finckh M, Poete P (2008) Vegetation Map of the Drâa Basin. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 31-32. Department of Geography, University of Bonn, Bonn

Gillson L, Hoffmann MT (2007) Rangeland Ecology in a Changing World. Science 315:53-54

Knippertz P, Christoph M, Speth P (2003) Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorol Atmos Phys 83:67-88

Quézel P, Barbero M (1981) Contribution à l'étude des formations présteppiques à genévriers au Maroc. Bol Soc Brot, Ser 2 53:1137-1160

Quézel P, Barbero M, Benabid A, Rivas-Martinez S (1994) Le passage de la végétation méditerranéenne à la végétation saharienne sur les revers méridional du Haut Atlas oriental (Maroc). Phytocoenologia 22:537-582

Quézel P, Barbero M, Benabid A, Rivas-Martinez S (1995) Les structures de végétation arborées à Acacia sur le revers meridional de l'Anti-Atlas et dans la vallée inférieure du Draa (Maroc). Phytocoenologia 25:279-304

Schmidt M (2003) Development of a fuzzy expert system for detailed land cover mapping in the Dra catchment (Morocco) using high resolution satellite images. Doctoral thesis, University of Bonn, Bonn

Schulz O (2008) Precipitation in the Upper and Middle Drâa Basin. In: Schulz O , Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 19-20. Department of Geography, University of Bonn, Bonn


EL ABIOUI



8 Anthroposphere

8.1 The societal framework of water management and strategies of livelihood security

8.1.1 Social organization, livelihoods, and politics of water management in Benin

8.1.2 Demographic development in Southern Morocco: Migration, urbanization, and the role of institutions in resource management

8.2 Economics of agriculture and water use

8.2.1 Climate and socio-economic impacts on Benin's agriculture

8.2.2 Hydro-economic processes and institutions in Southern Morocco

I-8 Anthroposphere

A. Kuhn and T. Heckelei

The anthroposphere may be defined as the part of the environment that is made or modified by humans. Put differently, the anthroposphere is the sphere of the earth system or its subsystems where human activities constitute a significant source of change through the use and subsequent transformation of natural resources, as well as through the deposition of waste and emissions. Since the end of the 18th century, population growth and the technology advances have made humans the dominant drivers of change to the earth system as a whole and most of its subsystems (Crutzen 2002)[1]. In low- and middle-income countries, human activities are still heavily based on the use of natural resources, renewable or non-renewable. The cultural habits, technological knowledge, and preferences determine the state and change of regional anthropospheres.

This chapter provides an overview on the state of the anthroposphere in two regions of research, Benin and Morocco, with special emphasis on the human use of water and land resources. The impact of selected demographic, anthropological, and economic characteristics and processes on resource use is given special attention – for instance, the importance of gender in household water use in rural Benin, or the frictions between the different institutional layers that govern the irrigation schemes in the Drâa valley of Morocco. In both regions, the knowledge gained about the processes governing the anthroposphere was entered into numerical simulation models with both biophysical and economic features. The features of these models are also briefly described.

[1] Crutzen PJ (2002) Geology of Mankind. Nature 415:23

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I-8.1 The societal framework of water management and strategies of livelihood security

M. Bollig and M. Rössler

Benin is one of the smaller countries of coastal West Africa. Dwarfed by its giant neighbor, Nigeria, the country displays a high degree of cultural diversity. Culturally and linguistically, communities of northern Benin differ from those in the southern parts of the country. Diversity also pertains to religious beliefs, with Muslims dominating in the north and Christians dominating in the south of the country. In many other African countries, cultural diversity is mirrored in ethnic maps (due to colonial tribalization policies); in Benin, however, cultural diversity permeates settlements and even households. Especially in the focal area of the IMPETUS project, communities are ethnically highly heterogeneous with often more than ten ethnic communities living in a settlement, and display hybrid institutions and beliefs. In recent decades, mobility has increased throughout the country. Although many men and women seek labor in neighboring Nigeria, the cities and plantations of southern Benin provide several attractions. A key point of interest for the IMPETUS project was the intensification of rural-rural migration, in which farmers from highly populated, resource-poor regions in the north venture to forested areas in the Ouémé catchment to open up lands for cultivation.

In Southern Morocco, the predominantly Muslim population is composed of berberophone and arabophone communities. Strategies of water management are strongly influenced by demographic processes, particularly by a high rate of emigration resulting from poor economic conditions in the rural areas. Although livelihood security in the oases of the Drâa catchment increasingly depends on income generated by migrants, agriculture and livestock breeding are still the principal economic activities of the local population. Both are regulated according to historically established, though often conflicting, patterns of land and water rights in the village communities. Practices of water management, as well as demographic trends in Southern Morocco are analyzed against the background of economic, social, and cultural institutions. It is shown that decision-making strategies related to resource management are not only shaped by climatic factors, but also by historically and culturally embedded institutions, as well as by the constraints of population dynamics.

I-8.1.1 Social organization, livelihoods, and politics of water management in Benin

K. Hadjer, B. Höllermann, and M. Bollig

Abstract

Water constitutes an integral component of human livelihood security. In Benin, the local management and use of scarce water resources has made necessary the application of multiple risk strategies to cope with uncertainty. Socio-scientific research over several years has identified a great variety of individual strategies for protecting one's livelihood. The patrifocal social structure, pronounced gender-differences and high degree of individualization constitutes the societal framework of livelihood strategies. Moreover, occult practices and related modes of secrecy concerning income have strong impacts on daily behavior. Individual networking, reciprocal gift exchange, and engagements in the risky cultivation of cotton emerge as popular strategies to minimize food insecurity. Especially in rural areas, agricultural production, the transformation of agricultural products and their exchange prove to be key activities that are dependent on water and water management systems. At the same time, the water supply sector lacks sufficient demand satisfaction. The reasons for this unsatisfactory supply are determined by physical constraints such as the seasonality. Moreover, socio-economic and institutional factors have been identified as the most limiting factors that prohibit safe access to water. Limited financial and technical resources prevent improvements. A lack of institutional structures on the village level and missing responsibilities concerning water management do not assure the maintenance of the available water resources (see sect. II-4.4). The main water users (households, industry, irrigation and livestock watering) pursue different strategies to satisfy their demands.

Keywords: livelihood security, risk strategies, economic activities, kinship, residence forms, income, vulnerability, occultism, land use, cash crop, gift exchange, water demand and supply, water consumption.

I-8.1.1.1 Introduction

This subsection provides an overview of central characteristics of the local society in Central Benin, with regard to their socially embedded livelihood strategies and their approach to satisfy water demand. Social science research on local livelihoods, adaptation strategies, and vulnerability emphasizes the capacities of people to apply innovative risk strategies (e.g., Boserup 1993; Smit and Wandel 2006). According to Chambers (1995), "livelihood refers to the means of gaining a living, including livelihood capabilities, tangible assets and intangible assets. Employment can provide a livelihood, but most livelihoods of the poor are based on multiple activities and sources of food, income and security". Like in many developing countries, the rural population of Benin adopts multiple economic activities to cope with uncertainty and seasonality of food supply.

Livelihood strategies of the Beninese population depend strongly on gender differences, intra-household heterogeneities, and occult practices (Hadjer 2009). Therefore, we start with a short insight into the social organization of households and the impact of occultism on income. We continue with research results on livelihood strategies and land use. As water constitutes an integral component of human livelihood security and economic activities in Benin depend on the utilization of water (Hadjer 2008a), we conclude the subsection by addressing water supply and demand.

I-8.1.1.2 Kinship, family and residence forms

The polygynous family

Strategies to ensure a population's livelihood are always embedded in the social organization of this population. In Benin, strategies of livelihood security are based on gender differentiation across ethnic divides, accentuated by the dominant practices of the patrilineal societies or ethnic groups. Filiation, succession, and naming follow these patrilineal rules. Residence patterns are virilocal, e.g., at marriage, the women move to their husband's home. After marriage, sons live frequently with their parents until sufficient capital is accumulated for the foundation of their own household. Polygyny is widespread. In the village of Bougou (department of Donga), 43% of married household heads live together with more than one wife. Among the monogamous household heads, up to half reported experiences as polygynous husbands. The average number of wives per husband is 1.2 (2004, see Hadjer 2009). This mean approximates the appraisal value of 1.3-1.5 wives per husband in West Africa (Kasmann and Körner 1992).

Women living in polygynous households continuously have to act in a world of shifting balances of power and hierarchies, where envy and competition pre-

vail. Nevertheless, many interviewed women emphasized the economic character of a polygynous household and judged disputes with their co-wives as conflicts over material support of their husbands, rather than as jealousies for his affective favor. Polygyny gives men an opportunity to accumulate prestige, improve status, and have a large number of children. Women can also profit from polygyny when household duties can be shared among co-wives, leaving room for individual economic activities. In polygynous households, women can leave the home regularly for several days to trade at markets in other villages or towns. Many women stress that this tradition allows for the accumulation of individual capital through trade made possible by the increased mobility. This economic independence and the option to create a business is rated so high by women that in some cases women left their husbands because they refused to marry a second wife.

A side effect of the patri-focus of the society is the strong normative pressure on men to guarantee the basic food supply of the family. Therefore, crop failure does not only jeopardize the family's food supply, but also weakens the social position of the husband, which can foster further tensions in the family, kin-group, or the larger social surrounding. If he cannot provide adequately for his wife, his authority is undermined. At the same time, the economic emancipation of women may lead to loss of status and legitimacy for their husbands.

Family and kinship

In the Beninese multiethnic society, kinship and family ties constitute the framework of social acting. They exist in conjunction or independently from intra-household relationships. The degree of networking and cooperation in times of crisis differs between the different levels of kin. It is high among married partners, parents and children, or between children with shared parents and less if paternal or maternal half-sibling or family-in-laws are concerned.

Kinship ties (*la parenté*) refer particularly to the patriline. These agnatic relationships could be characterized by respect, affection, and friendship, as well as by hierarchies and competition depending on the position of ego. Consanguinal kinship relationships, in general, represent a central and stable point of reference for each male or female individual. Affinal relationships are less stable. The importance of kinship in general becomes evident when problems have to be solved. This is particularly true for expenses for ceremonial occasions like ancestor worship, baptisms, or weddings, but also for conflicts within the family.

Households and residential units

Different behavioral options for male and female actors emerge from the great variety of local residence types and units, which are not necessarily congruent to households. In the following concepts, 'compound' and 'residential unit' are used syno-

nymously for a clearly-defined geographic area in which people live together and share a common courtyard. A residential unit can be composed of several households.

Within a residential unit a household exists if at least two of the following criteria are met: "a shared granary, a shared kitchen, or the collaborative cultivation of fields" (Hadjer 2009) A household resembles a survival community, in which members cooperate, but also run highly efficient individual economic activities – especially in the case of polygynous households. Thus, households are not productive or consumptive units but social structures in which individuals and strategic groups cooperate and compete.

Members of residential units can be of the same descent, have similar social networks and/or have the same group identity with other residential members. However, the cohabitation of individuals of different ethnic origin within one residential unit is common. Residence family ties are available for day to day decision-making, cooperation, help, and the satisfaction of basic needs. Bako-Arifari (2001) identifies (1.) single-household families in which the family can be equated with a production and consumption unit; (2.) extended single families in which a man presides over several generations and 'lower units' (e.g., married sons); and (3.) families consisting of several households that are subordinate to the authority of a single household head. In many villages and towns, further household compositions exist: (4.) Singles like widows, widowers, or women living apart from their husbands; (5.) tenants such as celibates or newcomers; (6.) people sharing a residence; and (7.) residence units with multiple household heads under one roof, but who keep their own economic activities and food separately (Hadjer 2009).

Paternal sons living with their wife (and children) in the fatherly household represent an important strategic group. They form core families within the residential unit and are subordinate, in many areas, to the household head. Thus, a son can live monogamously and his father polygamously, or vice-versa. This illustrates the difficulty of applying a single family structure to a so-called family household.

Compounds, houses or flats with women as heads of household represent a further type of residence. In the young village of Bougou, situated in Central Benin between Djougou and Bassila, 15% of all households are led by women, half of these by widows (n = 402, 2004). A further 40% are women living apart from their husbands (*foyer eclaté*). These women share the same roles, rights, and obligations with their co-wives in the husband's household, but live independently in their own houses. A further 10% of the female household heads in Bougou were single or divorced women (Hadjer 2009).

Every household is a hierarchically organized community with one or several (mostly male) head(s) at the top. Members can form sub-units and carry out economic activities independently. Generally, only a very small part of livelihood strategies is coordinated at the household level (e.g., harvesting). Women and men tend to work independently from each other and in many domains are even strictly separated. The pronounced gender differences, combined with the high degree of individualized strategies to earn and manage money, are key characteristics of strategies ensuring the security of local livelihoods.

Especially with the growth in household size and the multiplication of diverging capital accumulation interests, the danger of internal social and economic collapse is increasing. The deliberate maintenance of gender differences and infrastructure norms (like the separation of property or separate income management) has proven to limit personal power of the household head. This leads to a separation of property among women and men and to the fact that both control their own products. As a result, one can find a variety of different preferences and capital accumulation under one roof that encourages social differentiation and offers individuals the chance to fundamentally improve their economic situation.

The heterogeneity of affiliations found in the various households is echoed in the great variety of individual strategies for protecting one's livelihood. This encourages the establishment of individual networks that go beyond the household and kinship level and represent platforms of social exchange. One example is the close relationship of wives to their original families that live elsewhere.

I-8.1.1.3 Income and the impact of occultism

The high degree of individualization culminates in secrecy concerning individual income. Fear of jealousy and occult practices are behind it. Hadjer (2008b; 2009) describes that investments in the occult as a very common kind of risk-coping strategy in Benin. It is anticipated that lack of payments for protection charms and occult practices preventing aggressive jealous rivalries, for example, could lead to serious failure of health, fortune, or success. Financial investments in the protection against sicknesses, as well as expenditures for positive magical power, exist at all levels of society.

On the individual level, for example, a project assistant did not have the courage to continue the construction of his house without magical protection. He explained that this was due to his fear of envy, which could result in destructive sorcery. At the village level, the community may collectively evoke spirits to get rain or protection against negative spirits. Occultism proves to be an important component of livelihood strategies and daily social practices. At the same time, occult ceremonies and products can be very expensive. The costs involved may exceed the yearly mean income of a woman working in a market. Ritual charms or mediums are, for example, powder, soaps, or beverages, and recorded prices range from 15 € to 457 € for a single treatment.

In the village of Bougou, a high school graduate paid 23 € for a powder to help him pass an exam. This amount approximates the monthly salary of an elementary school teacher. Certainly, this very short account of a complex topic leaves a lot of questions unanswered. Occult practices have a strong impact on daily social and economic action, financial budgets and, therefore, on the livelihood strategies of the population.

I-8.1.1.4 Livelihood strategies and land use

Agriculture constitutes the most important set of activities in the center and north of Benin, where only 39% of the population lives in urban areas (INSAE 2003). While cotton production is highly risky due to fluctuating prices on the world market and changing national regulations, many people ensure their livelihoods by subsistence agriculture. The fact that agricultural production and the commercialization of agricultural products are closely interlinked necessitates intra-household cooperation between men – who dominate the agricultural domain – and women – who dominate commodity trade of agricultural products at local, national and international levels.

The view that women perform the bulk of agricultural work proves untenable for many parts of Benin. According to a regional survey conducted by the social scientists of the IMPETUS team,[1] twice as many men were engaged in cultivation and horticulture than women. The following survey questions, "What are your main economic activities? How do you ensure your livelihood?" and could you "Quote at most three activities?" revealed an average of 1.4 activities per man and 1.6 activities per woman.[2] As shown in table I-8.1.1, the spectrum of male economic activities is clearly dominated by agriculture, whereas the spectrum of female activities is dominated by food-processing (e.g., millet beer) and trade.

Men usually combine agricultural production during the rainy season with craft production or work in the service sector during the dry season. Only few women officially own land, and in some regions 'reaching for the hoe' is taboo. Additionally, trading of agricultural commodities is more lucrative and the incentives to extend agricultural activities are limited. Thus, women frequently generate revenue by a combination of commerce and the processing of agricultural products into commodities (e.g., butter, charcoal). This activity may already occur within the household. Animal husbandry is practiced predominantly by male Fulani.

As mentioned above, cultivation is central to ensuring food supply. The obligatory agricultural activities of women include sowing and harvesting. Yet, during the course of a year, this in no way represents the center of their daily labor activities, especially not in the towns. In local languages such as Yom, the influence of gender differences on concepts of work are reflected in a marked differentiation between the "work of man" (*dò-maayu*) and the "work of women" (*pòy-maayu*). Furthermore, some work (*maayu*) can be done by both sexes.

Certainly, motives and reasons for the diversification of income-generating activities are multiple (e.g., Gasson and Winter 1992; Giourga and Loumou 2006). However, people tend to maximize opportunities through diversification,

[1] Statistically representative gender-sensitive regional survey on livelihood security and resource use (2004); n = 839 (women and men) in 7 communities (Bassila, Djougou, Copargo, Ouake, N'Dali, Parakou, Tchaourou). See subsect. II-4.4.1.

[2] Only 6% of questioned people declared an absence of income by economic activities - senior men in rural areas (n = 12), female Muslims (n = 34). The pension rate is limited to six persons.

Table I-8.1.1: Economic activities (n = 1138) by sex (n = 774) in 2004 (Source: own survey).

Economic activities	men	women	total
Agriculture & Forestry			
Cultivation	256	122	378
Horticulture	105	29	134
Livestock breeding	29	12	41
Forestry	6	0	6
Total	396	163	559
Craft & Industry			
Small-scale processing of agricultural products and commercialisation	0	101	101
Industry	3	0	3
Craft	62	25	87
Total	65	126	191
Services			
Trade	30	283	313
Education	7	4	11
Health	18	2	20
Other	41	3	44
Total	96	292	388
Total	557	581	1138

in light of uncertainty caused by rain failure or an insecure and limited access to natural resources. Many perform several different economic activities ('polyactivities') in the course of a year to support themselves and their families.

The term polyactivity is especially used within the livelihood debate.[3] The high flexibility and mobility of the working population seems to favor a high level of adaptive capacities, in case of changes to the social-ecological system. For example, women adapt their transformation activities very creatively to the dynamics of demand and supply situations. Therefore, a producer of millet beer or shea butter will reduce her activities in times of water scarcity and switch to other activities as selling shoes or agricultural products.

[3] Also known as plurality of activities, moonlighting, MLES (**M**ultiple **L**ivelihood **E**conomic **S**trategies; MML) and MML (**M**ultiple **M**odes of **L**ivelihood). On polyactivity in Africa see Reardon et al. (1994) or Francis (2000).

I-8.1.1.5 Risk versus stability: Cash crop and gift exchange

In northern and Central Benin, two different livelihood strategies are very common: on the one hand, people become involved in reciprocal gift exchanges ensuring food supply and support in times of shortage. On the other hand, many peasants engage in the risky cultivation of cotton, with the objective of earning a lot of money at one time.

Male producers, especially, opt for the export-oriented cash-crop cultivation of cotton despite fluctuating world market prices and structural weaknesses of this still de facto, state-controlled sector. The one-time payout of high amounts of money adds zest to cotton production. The cultivation of the highly vulnerable plant demands time, discipline, calculative capacities, technical knowledge, and the credit for financial investments such as seeds, pesticide, fertilizer, or wage workers. These conditions involve considerable risk factors, such as unforeseen indebtedness and may lead to nutritional insecurity and intra-household conflicts.

The risk of cotton production

The food security of families is particularly endangered when producers neglect subsistence food production at the cost of cash-crop production. To the surprise of many small scale cotton producers, earnings are frequently lower than expected. This fact is due to external factors such as (1) rain failure causing low yield and a poor quality of harvest; or (2) declining world market prices causing low revenues; and internal factors such as (3) false calculations and (4) lack of comprehension of contracts and offers of subsidies due to illiteracy. Many farmers miscalculate derivative investment costs including wage labor, bribes or the loan from a pesticide distributor. The resulting imbalance between prospects, arrears and effective gains bring about debt, conflicts and – in case of neglected engagements in subsistence agriculture – food insecurity (Hadjer 2009).

A local proverb points to another risk factor, “No money disappears faster than the white money”. This saying refers to the exceptional status of cotton as a cash crop. In fact, high amounts of money may be earned in a short period. However, in a country where individual revenues are usually hidden and people seldom know exactly what the other earns, the open and highly visible display of cotton crops, in addition to the possible gains from cotton, proves to be an exception. Villagers can appraise the harvest of individuals or groups since their cotton is displayed openly in the form of pictorial white piles in the savannah landscape. Referring to norms of reciprocity, family members quickly claim their part of the gain individual farmers have made.

Generally, cotton producers cultivate separate field while participating in production or village groups. This involvement in cooperative activities is strongly encouraged by the state. Cotton producers have ambivalent opinions on the col-

lective organization of production. While some producers emphasize the advantage of lowering risk through pooling of resources, others describe their membership in cooperative activities as a handicap.

The cotton-crop calendar has to be applied strictly. Therefore, expenditure for wage workers is often inevitable. The government promotes parallel production of maize and cotton to avoid food insecurity. However, many farmers prefer to sell the subsidized maize seeds for money, hoping to reduce the amount of credits. Others practice an extended use of cotton fertilizers in maize production due to increasing soil degradation.

Generally, many women consider cotton production as a male domain because men have access to land and credits without the need of a custodian. However, over the past few years, women have become increasingly engaged in cotton production. The harvest time for cotton is very short, and any delay in the schedule affects the quality of the harvest. As the fields of their husbands have priority, women with individual fields would take the risk not to harvest their fields at the right moment. Contrary to men, therefore, they tend to farm together on collective fields. Collective farming makes it easier to organize the harvest schedule and to employ wage workers. Thus, the risk of missing the optimal harvesting time is minimized.

Gift exchange as a risk-minimizing strategy

When income is irregular, and the dependence on external factors (rain) is high, precautions have to be taken in order to weather times of shortage. The rural and urban populations attempt to cope with livelihood risks through complex networks of highly gendered gift exchange. This strategy is maintained equally in urban and rural areas and is applied throughout the year, mainly within extended families (Hadjer 2008c). Exchange outside the family takes place in a strictly gendered setting, between neighbors, friends, or colleagues (a priori of the same sex). The exchange of agricultural products, objects, money, or meals establishes social relationships and dependencies. Female engagement in food exchange is a key strategy to increase food security.

Donations of money constituted one third of all circulating gifts in the surveyed region. Monetary gifts circulated more frequently between men. In urban areas, land access is scarce; thus, the exchange of agricultural products occurs with the same frequency as the exchange of money. Generally, women exchange greater numbers of gifts in shorter time intervals, with higher frequencies and rates of reciprocity compared to men.

In sum, land use and livelihood security are highly linked to gender-specific risk strategies. Agricultural production, the transformation of agricultural products and their exchange prove to be key activities that are dependent on water and water management systems. Apart from domestic needs, a third of the population of Central Benin requires water for productive activities. Thus, many people's economic activities in Benin depend on the utilization of water.

I-8.1.1.6 Water demand and supply

Compared to the water supply sector in developed countries, the water supply sector in African countries usually lacks sufficient demand satisfaction, concerning both quantity and quality (Niemeyer and Thombansen 2000). Even though efforts are being undertaken to improve the situation, the economic and physical conditions adversely affect obtaining an optimal supply of water, especially potable water. The domestic water supply in Benin is no exception. From a statistical perspective, Benin's urban population has reasonable access to water for domestic purposes (Gruber et al. 2009), but the water situation in rural Benin is not satisfactory. IMPETUS studies revealed that the daily water consumption in rural areas of Benin is less than 20 L/cap/d (Schopp 2004; Hadjer et al. 2005), which is the absolute minimum a person requires to fulfill basic human needs (WHO 2003). Furthermore, the water quality of many water pipes is alarming.

Strategies of Beninese water users to satisfy water demand

Households, industry, irrigation systems, and livestock present the main water users in Benin. These user types are described below in more detail, explaining the amount of water used and their strategies to satisfy these requirements.

The domestic water demand highly depends on the water source being used. The shorter the distance from a source to its site of demand and the more immediate the access to a source, the greater is the chance that the demand will be satisfied (Schopp 2004; Hadjer et al. 2005). Three distinct sources are distinguished: tap water, water from a well or water tower, and water from the river. According to IMPETUS studies by Schopp (2004) and Gruber et al. (2009), the amount of water consumed from rivers is 14 L/cap/d and from wells 19 L/cap/d. However, during the dry season these small amounts even decrease as surface water becomes more rare and shallow wells run dry (Schopp 2004; Behle 2005). SONEB (*Société Nationale des Eaux du Bénin*) is the national tap water supplier and maintains 69 supply systems in urban areas. The urban water demand supplied by SONEB ranges from 57-80 L/cap/d (Christoph et al. 2008). However, it is common practice for households with a house connection for SONEB water to resell the tap water to the unconnected neighbors. To estimate Benin's domestic water demand, information concerning the frequency of the used water sources was needed; information from every village was available from the 2002 census data (INSAE 2003). Figure I-8.1.1 summarizes the annual domestic water demand per *Commune* for 2002.

SONEB water is either pumped from deep groundwater or supplied by surface water from reservoirs (e.g., in Djougou, Parakou and Savalou). The price for SONEB water is fixed for all cities; however, two price schemes exist based on the amount of consumption. Households with low demand have to pay 198 FCFA/m³ (~0.30 €/m³) for the first 5 m³/month. The price for monthly demand greater than

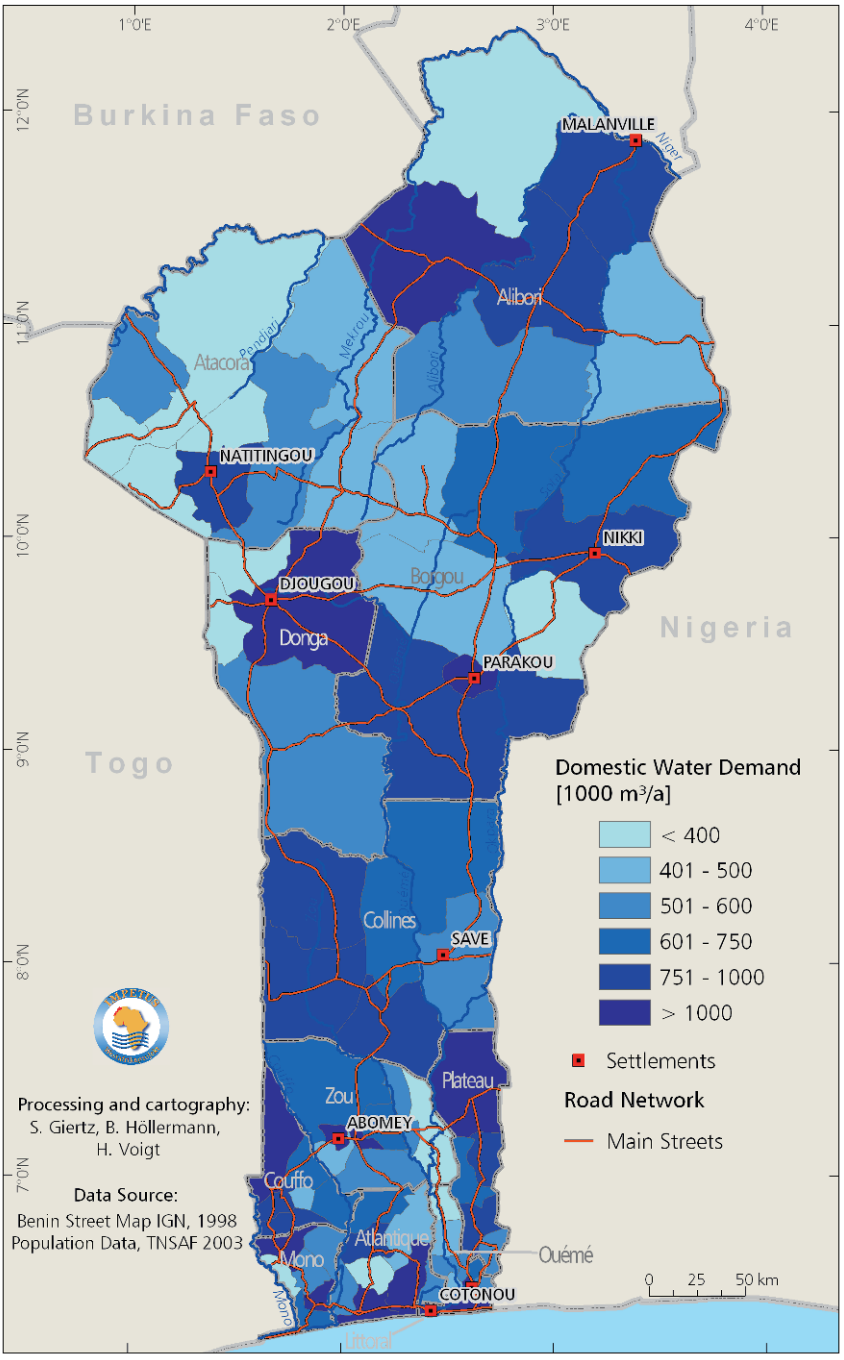

Fig. I-8.1.1: Annual domestic water demand per commune in 2002.

5 m³ is 415 FCFA/m³ (~0.63 €/m³). Therefore, for a household size of 6 persons, the lower tariff allows consuming 28 L/cap/d, ensuring that poorer families can afford a reasonable amount of filtered and purified SONEB water. Wealthier households and industries that have higher water demands, therefore, pay higher prices for this 'social' tariff, ensuring the viability of SONEB and re-investment into the supply system (Niemeyer and Thombansen 2000).

The *Ministère des Mines, de l'Energie et de l'Hydraulique* (MMEH) and its *Direction General d'Eau* (DGEau) are responsible for Benin's water resources management and the rural water supply, including the cities not served by SONEB. This responsibility comprises the establishment of rural water supply systems e.g., wells built with the support of development collaborations (Niemeyer and Thombansen 2000). Therefore, rural and urban households not served by SONEB use water from water towers, protected or unprotected wells, pumps either driven by hand, feet, solar, or diesel, as well as *marigots*[4] and rivers to meet their water demand (Schopp 2004). Usually women are responsible for supplying the household with water (see subsect. II-4.4.3). In cases where no house connection exists, the women have to fetch the water. In contrast to the urban water supply, the economic situation of a rural household does not determine the water source to be used. The preference for a distinct source depends on the availability and constraints set by the season and time involved in fetching water, which could be

Table I-8.1.2: Water consumption and supply strategies on department level (Source: own calculations based on data provided by INSAE 2003; Schopp 2004; Behle 2005).

		Share of water sources used in (2002)		
Department	**Annual water demand in Mm³**	**SONEB (Groundwater and reservoir**	**Well and pumps (Groundwater)**	**Marigôts and rivers (surface water)**
Alibori	3.9	4	78	18
Atacora	4.1	5	69	26
Atlantique	9.4	19	69	12
Borgou	6.8	11	65	23
Collines	4.5	11	75	14
Couffo	4.7	15	67	18
Donga	2.7	5	68	27
Littoral	19.0	97	3	0
Mono	4.3	29	62	9
Ouémé	9.0	25	57	18
Plateau	4.0	19	54	27
Zou	7.5	27	39	34
Sum	79.9	22	59	19

[4] Marigots are swales or periodically water-bearing side arms of small rivers (Schopp 2004).

Table I-8.1.3: Industrial water demand in 2002 (Source: own calculations, Höllermann et al. 2009, based on data provided by Schopp and Kloos 2007).

Department	Annual Water Use Rate [m^3] specified after industrial classes, number in brackets equal number of businesses					
	Textile industry	Food industry	Chemical industry	Hotel Business	Agro-industry	Sum
Alibori	41,052 (3)	3,468 (1)	-	88,264 (8)	9,247 (1)	142,031 (13)
Atacora	13,648 (1)	13,872 (4)	2,685 (1)	231,693 (21)	-	261,934 (27)
Atlantique	-	31,098 (10)	-	77,231 (7)	119,615 (8)	227,944 (25)
Borgou	58,203 (5)	46,178 (13)	2,685 (1)	233,140 (23)	745 (2)	340,951 (44)
Collines	65,935 (3)	38,294 (12)	-	88,264 (8)	9,247 (1)	201,740 (24)
Couffo	13,648 (1)	-	2,685 (1)	-	18,494 (2)	34,863 (4)
Donga	-	3,468 (1)	-	33,099 (3)	-	36,567 (4)
Littoral	89,195 (13)	205,093 (84)	109,856 (39)	567,405 (46)	18,497 (6)	990,046 (188)
Mono	50,937 (2)	3,468 (1)	-	99,297 (9)	-	153,702 (12)
Ouémé	1,285 (2)	165,072 (20)	2,923 (3)	89,108 (10)	9,407 (2)	267,795 (37)
Plateau	13,684 (1)	20,808 (6)	2,685 (1)	33,099 (3)	9,247 (1)	79,523 (12)
Zou	131,291 (4)	27,518 (9)	-	37,138 (5)	84,863 (6)	280,810 (24)
Sum	478,950 (35)	558,337 (161)	123,519 (46)	1,577,738 (143)	279,362 (29)	3,017,906 (414)

quite time consuming (Hadjer et al. 2005; Behle 2005). For example, the women of the village Sérou prefer to fetch water from the well or *marigot* because the distance to the pump is greater; hence the pump is only frequented during dry seasons (Schopp 2004). Furthermore, at the pump women have to fetch the water one at a time, increasing the time expenditure significantly (Behle 2005). Although the women are aware of the poorer water quality of the well and *marigot* water, they prefer it.

Table I-8.1.2 summarizes the amount of consumed water and the fractions of the used water sources by department and according to the above-mentioned preferences and different supply opportunities reflected by the regional disparities within the country.

Due to its low degree of industrialization, the water demand from the industrial sector is not very different from most businesses found in the south, in contrast to

other sectors with low water demands. A comprehensive survey by Schopp and Kloos (2007) captured all industrial and service businesses (414) and analyzed the water demand of 168 of them with SONEB water bills. The different industrial branches (excluding the energy branch due to a lack of data) have been classified into five classes according to Adam and Boko (1993): textile industry, food industry, chemical industry, hotel business, and agro-industry. Based on the surveyed annual water use rates, means for each class were calculated and applied to the other listed industries, allowing a comparison of the distribution of water demand per industrial sector among different departments (Höllermann et al. 2009; see table I-8.1.3).

The survey by Schopp and Kloos (2007) further revealed that the industrial branches satisfy 90% of their demand with SONEB water (60%), well (20%), and pumps (10%). The remaining 10% of water demand are supplied by rainwater collections.

The agricultural water demand includes irrigation and livestock watering. In Benin irrigation is not widespread, and most of the agricultural activity is rain-fed (Mulindabigwi 2005). The irrigated area is distinguished into three types: large-scale irrigation, urban and peri-urban horticulture, and inland-valley irrigation. Only five larger irrigation schemes exist (Malanville, Savé, Dogbo-Tota, Pobe and Za-Kpota) for cultivating sugarcane, rice, and palm trees. The urban and peri-urban horticulture is irrigated year round, and produces mainly tomatoes, okra, and onions (Gruber et al. 2009). In contrast, irrigation of inland-valleys occurs

Table I-8.1.4: Irrigated agricultural areas in the départments of Benin [ha] (Source: own calculations based on data provided by Kloos 2006; Giertz et al. 2007; Gruber et al. 2009).

Department	Size of irrigated area [ha]			
	Inland-Valley irrigation	Large scale irigation	Urban / periurban horticulture	Total irrigated area
Alibori	401	350	706	1,457
Atacora	296	-	-	296
Atlantique	134	-	136	270
Borgou	181	-	478	659
Collines	444	975	-	1,419
Couffo	22	150	-	172
Donga	346	-	170	516
Littoral	-	-	1	1
Mono	52	-	75	127
Ouémé	141	-	7	148
Plateau	24	19	-	43
Zou	39	96	28	163
Sum	2,080	1,590	1,601	5,271

only during the dry season, with cultivation of mainly tomatoes, okra and pepper. Due to their physical properties (high rates of interflow and high groundwater levels), inland-valleys are saturated during the rainy season and best suited for cultivating rice (see sect. I-6.1 and Giertz et al. 2007).

While the irrigation water for large scale irrigation is derived from surface water (reservoirs or river water), inland-valley irrigation uses shallow groundwater, and urban and peri-urban horticulture uses fractions of both (Kloos 2006; Giertz et al. 2006, 2007).

Another important consumer of water in agriculture is livestock. While the southern part of Benin livestock farming is dominated by pigs, goats, and poultry, the north is dominated by cattle (van den Akker 2000). Here a distinct pattern of transhumance is practiced. Akpaki (2002) describes four different types of livestock migration: three short-distance migration cycles depending on yearly rainfall characteristics and agricultural activities and one long-distance migration cycle during the dry season, which includes migration from neighboring countries, especially from Niger. However, pastoralists do not take part in every migration and in most cases not with the whole herd. This strategy minimizes the risk of losing the entire herd e.g., in cases of disease, and allows the pastoralist to protect specific pasture areas against agricultural land use (see subsect. II-4.4.3). The water demand for livestock has been estimated by Gruber (2008) on the departmental level, taking into account the amount of livestock, as well as surface and economic restrictions. Table I-8.1.5 highlights the regional disparities of water demand reflecting the differences in composition and amount of livestock.

While in South Benin, livestock water demand is mostly met by groundwater, livestock watering in Central and North Benin is supplied by the surface water

Table I-8.1.5: Water demand of livestock in 2000 (Source: own illustration based on data provided by Gruber 2008).

Department	Water demand of livestock in 1,000m³/a (year 2000)
Alibori	8,016
Atacora	3,940
Atlantique	802
Borgou	6,884
Collines	1,186
Couffo	623
Donga	1,086
Littoral	170
Mono	413
Ouémé	656
Plateau	529
Zou	533
Sum	24,838

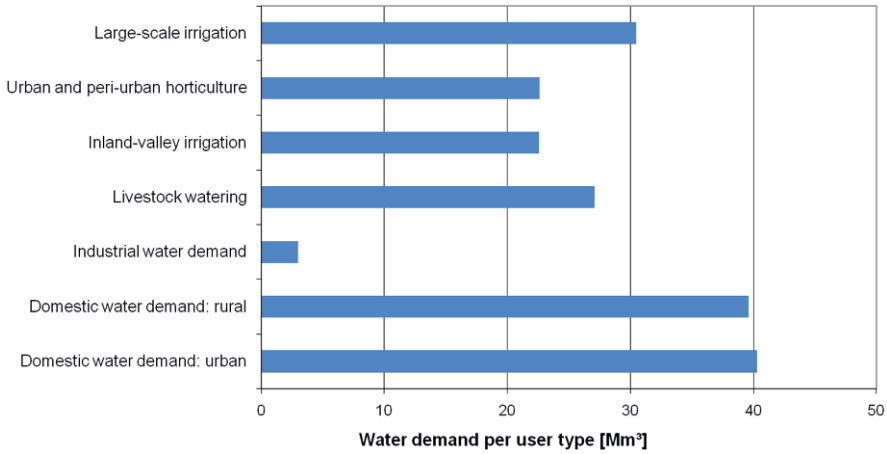

Fig. I-8.1.2: Water demand per user type in Benin in 2002 (Source: own calculations based on data provided by Schopp 2004; Giertz et al. 2006; Giertz et al. 2007; Schopp and Kloos 2007; Gruber et al. 2009).

from many small reservoirs built throughout the country (Gruber 2008). However, these reservoirs tend to dry up at the end of the rainy season, increasing the pressure and competition for the water resources.

Limitations and constraints of an optimal water supply in Benin

Given that the annual renewable water resources in Benin reach about 4,000 m³ per person, of which less than 5% is used (see fig. I-8.1.2). Therefore, one could argue that there are no water supply problems in Benin. However, as the above cited studies have shown, there is a lack of water supply and the amount of available water is less than the required minimum to fulfill basic human needs (Gleick 1996). The reasons for this unsatisfactory supply are determined by physical, socio-economic, and institutional constraints.

One important physical constraint is the seasonality of the water supply, caused by the distinctive dry and rainy seasons. Furthermore, the groundwater in the crystalline basement occurs only in preferential fractures and, therefore, is limited (Chilton and Foster 1993), resulting in seasonal drying-up of wells (Behle 2005). In addition, tapping those groundwater bubbles is quite expensive and bears the risk of tapping dry holes.

Socio-economic and institutional factors have been identified as the most limiting factors to a safe and reasonable access to water. Limited financial and technical resources prevent improvements in this sector. For example, the actual degree of rural water supply falls far below the potential of 60% because about 20% of the public standpipes are nonfunctional due to broken pumping systems (Niemeyer

and Thombansen 2000). As most standpipe projects require contribution from the community, which often cannot be obtained, many projects are not implemented. The lack of institutional structures and adherence to responsibilities on the village level, with respect to water management, prevents the maintenance of the available water resources, as well as re-investment into the supply system (Behle 2005).

I-8.1.1.7 Conclusions

In conclusion, the problems of Benin's water sector are challenging, and the importance of successful integrated water resource management becomes evident (see also sect. II-4.4). Many economic activities and livelihood strategies of the local population directly depend on water. The high flexibility and mobility of the working population seems to favor a high level of adaptive capacities when changes occur within the social-ecological system.

People tend to maximize opportunities through diversification when presented with uncertainties due to drought or insecure and limited access to water. Many people perform several different economic activities during the course of the year to support themselves and their families. Generally, the heterogeneity of types of residence is echoed in the great variety of individual strategies for protecting one's livelihood. Thus, gendered gift exchange reveals as a key strategy to cope with livelihood risks. On all societal levels, occult practices have a strong impact on daily social and economic action and intervene delicately in the financial budgets of the Beninese population.

References

Adam KS, Boko M (1993) Le Bénin. EDICEF, Cotonou

Akpaki JA (2002) Ackerbauern und mobile Tierhalter in Zentral- und Nord-Benin. Landnutzungskonflikte und Landesentwicklung. Reimer, Berlin

Bako-Afrari N (2001) Etude de milieu pour servir de base a L'élaboration d'une nouvelle stratégie d'appui aux producteurs dans le Département du Borgou à partir de quatre villages de la Sous-Prefecture de N'Dali. Synthèse des résultats. UNB, Cotonou

Behle C (2005) Ländliche Trinkwasserversorgung in Benin unter besonderer Berücksichtigung der nationalen Versorgungsstrategie "Alimentation en eau potable et assainissement en milieu rural". Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/ landw_fak/2006/behle_cornelia/0598.pdf. Accessed 23 October 2009

Boserup E (1993) The conditions of agricultural growth: The economics of agrarian change under population pressure. Earthscan Publications Ltd., London

Chambers R (1995) Poverty and livelihoods: whose reality counts? Environ Urban 7: 173-204. http://eau.sagepub.com/cgi/content/abstract/7/1/173. Accessed 12 November 2009

Chilton PJ, Foster SSD (1993) Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa. Hydrogeol J 3:36-49

Christoph M, Fink AH, Diekkrüger B, Giertz S, Reichert B, Speth P (2008) IMPETUS: Implementing HELP in the Upper Ouémé Basin. Water SA 34:481-490

Francis E (2000) Making a living: Changing livelihoods in rural Africa. Routledge, New York

Gasson R, Winter M (1992) Gender relations and farm household pluriactivity. Elsevier Science, London

Giertz S, Steup G, Gaiser T, Srivastava AK (2007) Nutzungspotential von Inland-Valleys im Oberen Oueme Einzugsgebiet. In: Integratives Management Projekt für einen Effizienten und Tragfähigen Umgang mit Süßwasser in Westafrika: Fallstudien für ausgewählte Flusseinzugsgebiete in unterschiedlichen Klimazonen. Achter Zwischenbericht, pp. 80-91. http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/IMPETUS_Zwischenbericht_2007.pdf. Accessed 14 January 2010

Giertz S, Steup GS, Stadler Ch, Schönbrodt S, Diekkrüger B, Goldbach H (2006) Analysis and evaluation of the agro-potential of inland valleys in the Upper Ouémé catchment (Benin, West Africa). Paper presented at Tropentag 2006. Conference on International Agricultural Research for Development, University of Bonn, October 11-13, 2006

Giourga C, Loumou A (2006) Assessing the impact of pluriactivity on sustainable agriculture. A case study in rural areas of beotia in Greece. Env Manag 37:753-763

Gleick PH (1996) Basic Water Requirements for Human Activities: Meeting Basic Needs. Water Int 21:83-92

Gruber I (2008) The impact of socio-economic development and climate change on livestock management in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2008/gruber_ina/1388.pdf. Accessed 23 October 2009

Gruber I, Kloos J, Schopp M (2009) Seasonal water demand in Benin's agriculture. J Environ Manage 90(1):196-205

Hadjer K, Klein T, Schopp M (2005) Water consumption embedded in its social context, northwestern Benin. Phys Chem Earth 30:357-364

Hadjer K (2009) Geschlecht, Magie und Geld. Sozial eingebettete und okkulte Ökonomien in Benin, Westafrika. LIT, Berlin

Hadjer K (2008a) Regional Survey: Economic Dependence on Water. In: Judex M, Thamm HP (eds) IMPETUS Atlas Benin: Research results 2000-2007. 3nd edn., pp. 53-54. Department of Geography, University of Bonn, Bonn

Hadjer K (2008b) Occultism and its Impacts on Economic Behaviour. In: Judex M, Thamm HP (eds) (2008) IMPETUS Atlas Benin: Research results 2000-2007. 3nd edn., pp. 119-120. Department of Geography, University of Bonn, Bonn

Hadjer K (2008c) Central Issues of Social and Economic Behaviour in Benin. In: Judex M, Thamm HP (eds) (2008) IMPETUS Atlas Benin: Research results 2000-2007. 3nd edn., pp. 117-118. Department of Geography, University of Bonn, Bonn

Höllermann B, Diekkrüger B, Giertz S (2009) Bewertung der aktuellen und zukünftigen Wasserverfügbarkeit des Ouémé Einzugsgebiets (Benin, Westafrika) für ein integriertes Wasserressourcenmanagement mit Hilfe des Entscheidungsunterstützungsmodell WEAP. Hydrol Wasserbewirts 53(5):305-315

Institut National de la Statistique et de l'Analyse Economique (INSAE) (2003) Troisième Recensement Général de la Population et de l'Habitation. Internal governmental data set, Cotonou

Kasmann, E, Körner M (1992) Autonom und abhängig. Westafrikanische Landfrauen zwischen Tradition und gesellschaftlicher Modernisierung. Bielefelder Studien zur Entwicklungssoziologie, 52, Saarbrücken

Kloos JR (2006) Analyse der Wassernachfrage im landwirtschaftlichen Sektor in Benin und Perspektiven der Bewässerung. Master thesis, University of Bonn, Bonn

Mulindabigwi V (2005) Influence des systèmes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2006/mulindabigwi_valens/0784.pdf. Accessed 23 October 2009

Niemeyer RG, Thombansen C (2000) Instrumente der Reinvestitionsplanung für die städtische Trinkwasserversorgung in Benin/Afrika. Wasser & Boden 52:37-43

Reardon T, Crawford E, Kelly V (1994) Links between Non-farm Income and Farm Investment in African Households: Adding the Capital Market Perspective. Am J Agr Econ 76:1172-1176

Schopp M, Kloos JR (2007) Wassernachfrage der Sektoren (Haushalt, Industrie und Landwirtschaft) unter Berücksichtigung möglicher Wasserkonflikte. In: IMPETUS (eds) Integratives Management Projekt für einen Effizienten Umgang mit Süßwasser in Westafrika. Achter Zwischenbericht. pp. 102-112.
http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/IMPETUS_Zwischenbericht_2007.pdf. Accessed 14 January 2010

Schopp M (2004) Wasserversorgung in Benin unter Berücksichtigung sozioökonomischer und soziodemographischer Strukturen - Analyse der Wassernachfrage an ausgewählten Standorten des Haute Ouémé. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2005/schopp_marion/0526.pdf. Accessed 24 July 2009

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Global Environ Chang 16:282-292

van den Akker E (2000) Makroökonomische Bewertung der Auswirkungen von technischen und institutionellen Innovationen in der Landwirtschaft in Benin. Doctoral thesis, University of Hohenheim, Stuttgart

WHO (2003) The Right to Water, Health and Human Rights 3.
http://www.who.int/water_sanitation_health/rtwrev.pdf. Accessed 24 July 2009

I-8.1.2 Demographic development in Southern Morocco: Migration, urbanization, and the role of institutions in resource management

M. Rössler, H. Kirscht, C. Rademacher, and S. Platt

Abstract

The societal development of Southern Morocco is characterized by the ambiguity between a dynamic population development and the persistence of traditional structures. Over the centuries, ideas and traits brought into Morocco by foreign immigrants had a strong influence on the social, political, and religious development of the region. Nevertheless, old Berber customs – especially those regarding local institutions and the management of natural resources – have survived in the retreating areas of deserts and mountain ranges. During the colonial period, tribes or descent groups lost most of their political power, but even today, their influence on village and resource management decisions remains strong. Although the state formally controls the territory through various agencies, a *de facto* plurality of juridical domains exists on the local scale.

The most significant alterations of society in recent years is modernization associated with the strong growth of urban centers and the experiences of large parts of the population gained through labor migration or contact with migrants. In addition, remittances changed the income or wealth structure of rural areas and thus, the social structure of many villages.

Keywords: Society, Berber, history, population development, labor migration, traditional institutions, state institutions.

I-8.1.2.1 Introduction

The mountainous areas and the region south of the Atlas Mountain chain have been economically marginalized for a long time. The Upper and Middle Drâa catchment belongs to the provinces of Ouarzazate (population: 498,000) and Zagora (population: 283,000), with their homonymous, fast-growing capital cities. In the Ouarzazate province, the population is predominantly Berber, while in the Zagora province, there are villages with berberophone and arabophone populations next to each other, as well as mixed villages. As elswere in Morocco, the

population is predominantly Muslim. After the last exodus in the 1970s, the historically important Jewish minority is practically non-existing. Permanent settlement in towns and villages are close to the tributaries of the Wadi (*Oued*) Drâa, while nomadic or transhumant pastoralists roam the vast territories outside the oases that are sparsely covered with vegetation.

I-8.1.2.2 Ethnic, social, and cultural background

The history of the region is characterized by various waves of immigration, which led to the present ethnic distribution. The Middle Drâa valley in particular, as the northern end of economically important trans-Saharan trade routes, was often contested, but the region south of the Atlas Mountains remained independent from the northern Moroccan kingdoms for a long time. Between the 8th and the 13th centuries, different Arab groups entered the region, subjugated the local sedentary population and expelled many nomadic groups. It was also a setback for Jewish traders who previously controlled the trans-Sahara trade. The region was Islamized.

During the 13th century, *Maqil*-Arabs conquered the Drâa valley. After a century, large parts of the tribe moved further north, leaving some fractions behind. The *Ouled Yahya* are their descendants. The region was not peaceful, and the *Ait Atta* Berber competed with the Arab *Ouled Yahya* and *Ruha* for the land and water resources. During the 16th century, the establishment of Sufi brotherhoods and the settlement of *Mrabtin* und *Shurfa* – descendants of the prophet Mohammed (Shurfa) or Islamic Saints (Murabtin) – led to the foundation of a new dynasty, the *Saadiens*. The *Saadiens*, descendants of an oriental sharifian family who had lived in the Drâa valley since the 14th century, were able to gain control over the caravan trade and extended their rulership over large areas of Morocco (El Moudden 2002). One consequence of their rule over and conquest of sub-Saharan Africa was an extended slave trade, which brought many Africans to the Drâa valley. Some authors claim that the darker-skinned Drawa and Haratin populations of the Drâa valley were descendants of slaves who were deported to the valley during the time of slave trade (Zainabi 2003). Even in postcolonial times, *Mrabtin* and *Shurfa* families were important political and social actors in the south, and only recently lost some of their influence.

The Berber population in the northern part of the Drâa catchment, especially the mountainous tribes, was less affected by Arab influences or domination. The segmented and acephalous socio-political structure of their society has been preserved to date, and strong tendencies for fission prevented lasting alliances. A remarkable exception is the *Ait Atta* confederation, which was strong enough to resist the French colonial troops for years (Hart 1984).

The socio-political organization of the Berber tribes is not an ideal example of a segmentary society. If economic or political action is required, territoriality, i.e., belonging to a certain territorial unit such as a village, is as important as descent

or genealogical affiliation. Furthermore, the village community controls access to the most important economic resource, the *tamazirt* or village land. The *tamazirt* includes the irrigated fields and the communal land or *agdal n'igram*, where villagers and nomads herd their cattle and where rain-fed agriculture is possible, at least in some regions.

Although political changes during colonial and postcolonial times were radical, the loss of the political and military functions of the Berber and Arab tribes, as well as the associated increase in power of the central government during the so-called "pacification" of Southern Morocco in the 1920s and 1930s, has not destroyed the traditional segmented structure of the tribes. Attempts have been made by colonial authorities to formalize informal Berber institutions, like the *amghar* (an elected mediator and leader), into a more centralized *jmaa* (tribal assembly). This would allow Berber tribes "to remain governed and administered in accordance with their own laws and customs" (Pennell 2000). The attempt of the colonial authorities to weaken Arab and Berber influence and to enhance control by creating new leaders has had only limited effects. After independence, the fragmentation of Berber tribes remained strong, leaving local communities as principal cooperative units and political actors. Nevertheless, tribal identities and the idea of a common assembly persist at different levels, especially where a pronounced territoriality is present.

I-8.1.2.3 Population development

Urbanization

An anthropological analysis of how water and land use affect the living conditions in the catchment area of the Drâa requires examining the local population dynamics, which is a result of, and an important driving force for economic and social change. In recent years, the intensified emigration from marginalized rural communities into urban centers became the most significant demographic phenomenon. In search for an alternative income, people migrate not only on national and international levels, but also regionally. There are many reasons for migration. Besides the deteriorating economic situation influenced by population growth, the declining labor demand of the agricultural sector and the absence of alternative income opportunities, individual motives of migrants play a significant role. These motives are often rooted in the social structure of the home villages (see subsect. II-5.4.1). The increasing water scarceness, especially for irrigation purposes, puts further pressure on the ability to farm successfully and reduces income and labor demand in the agricultural sector. As a result, migration and urbanization tendencies can be interpreted as important responses to population growth and the increasing water scarceness. Both factors play significant roles in the demographic development of the region.

The demographic dynamics of a society are determined by different but interdependent factors. Urbanization and migration influence the fertility and age structure by modifying reproductive behavior.

According to recent studies, Morocco shares many characteristics with other "labour frontier countries" (Courbage 1995). The current period of demographic transition is characterized by a still high but declining population growth, due to decreasing birth rates (Courbage 1995; de Haas 2003). Comparing age pyramids of the years 1960, 1982, and 2000, Ragala identified a trend toward a constriction of the base of the pyramid in recent years, due to a declining fertility rate. The current "*explosion démographique*" (Ragala 2002) will lead to an increasing number of older people in the future. Yet, the population is still very young; nationwide, 41.9% are younger than 20 years of age, while the population in the region under investigation is even younger: 47.9% and 53.2% of the population in the Ouarzazate and Zagora provinces, respectively, are below the age of 20 (*Haut Commissariat au Plan* 2005). The development of the population size in the catchment area of the Drâa can be analyzed from the national census data of 1994 and 2004 (*Direction de la Statistique* 1995; *Haut Commissariat au Plan* 2005).

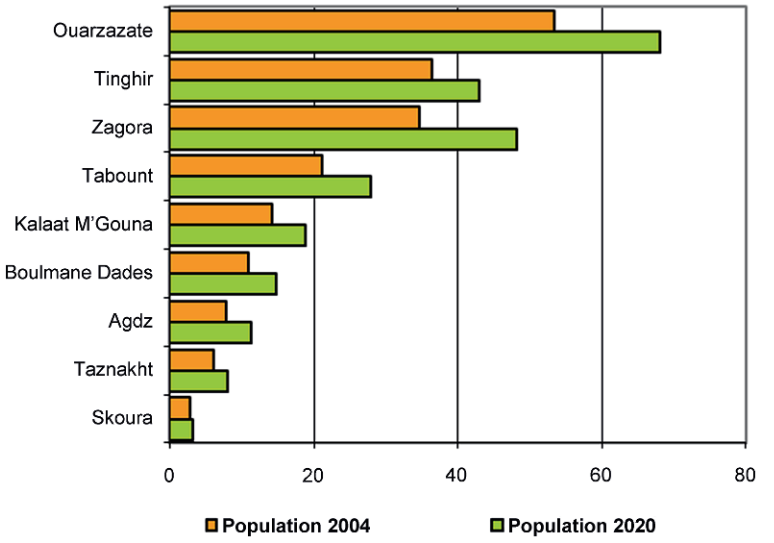

Fig. I-8.1.3: Projected population development. Urban area provinces of Ouarzazate and Zagora.

The spatial distribution of population growth is highly heterogeneous. In some areas, population growth even reaches negative values. Apart from international migration and a circular labor migration toward the thriving urban agglomerations of the north, regional migration movements from the most marginalized areas into the increasingly urbanized communes along the Drâa and the Dadès are found

more frequently (see fig. I-8.1.3). The consequence is the increasing urbanization of the already urbanized communities in the Ouarzazate and Zagora provinces, which offer income alternatives to subsistence-oriented agriculture, particularly within the tourism sector.

The main push factors for increased migration are the poor economic and infrastructural basis in the rural communities, and these were aggravated by water scarcity in recent years. The pull factors, besides diversified economic possibilities, are better infrastructure in education and supply of convenience goods in the regional urban centers. The urbanized areas in the region, therefore, play a crucial role in the overall demographic development. Between 1994 and 2004, the nine urban areas of the region grew much faster (3.1% average annual growth) than the rural communities (0.8%).

The future size of the population of the regional urban agglomerations in the catchment area of the Drâa was projected into 2020, based on the 2004 national census data, using the numeric model SPECTRUM/Demproj (POLICY Project; The Futures Group International 1997; Stover and Kirmeyer 2005). In 2004, their population ranged from 2,800 inhabitants in Skoura to 53,500 in Ouarzazate. The 187,800 inhabitants represent 24.1% of the entire population in the provinces of Ouarzazate and Zagora (Platt 2008). According to SPECTRUM/Demproj projections, this figure will rise to more than 240,000 inhabitants in the year 2020. The four largest urban areas, Ouarzazate, Tabount, Zagora, and Tinghir account for 77.6% of the urban population and 18.7% of the whole population in both provinces. Regarding the close projection goal for the year 2020, small significant changes in population trend and distribution should be registered because demographic processes react slowly to changes in the initial parameters. Therefore, disproportional population growth is not anticipated in the near future.

To summarize, the rural provinces of Ouarzazate and Zagora compared to the prospering regions in the northwest of Morocco, are generally characterized by a low population density, as well as by slow rural and fast urban population growth. The majority of the population is and will remain young. The most significant trends in population dynamics include increasing emigration and urbanization due to high reproduction and postnatal mortality rates.

Labor migration

Morocco has long been characterised by both international and national migration. Since the early 20th century, four different patterns of mobility have been characteristic, especially for the southeastern parts of Morocco: 1) the movement of itinerant craftsmen and traders; 2) seasonal migration at harvest times; 3) national labor migration; and 4) international labor migration.

International migration to France started during World War I, when mine workers and soldiers were recruited. The same development took place during and after the Second World War. During the Algerian war of independence (1954-1962),

Table I-8.1.6: Moroccan Population living abroad in 2005 (Source: De Haas 2006).

Country	Number of Migrants 2005
France	1,025,000
Spain	397,000
Netherlands	315,000
Germany	99,000
Scandinavian Countries	17,000
Great Britain	50,000
USA	85,000
Canada	70,000

the number of Moroccan migrants in France rose from 20,000 to 53,000. Most of them were working in mines and the steel industry. Since the 1960s, large-scale migration to the Netherlands, Germany, Belgium, and of course France, was evident (Obdeijn 1993). In the 1980s, Spain and Italy have also become important destinations. The number of Moroccans abroad has been increasing since the mid-1960s due to recruitment by European countries during the 1960s and 1970s. Even after the restrictive migration policies of the EU, the number of Moroccans in Europe has been rising. The mean increase of 50,000 migrants per year was partly due to family reunification and family formation, but illegal and undocumented labor migration has also been a significant contributor (de Haas 2003). Due to the economic recession and the tightening of immigration policies after the 1973 oil crisis, many migrants remained abroad, and relatively few Moroccan migrants returned home.

During the last decades, remittances from international migrants have been an important, continuous, and increasing economic factor for the Moroccan state. The $ 3.6 billion in repatriated funds sent home by migrants in 2003 represented 6.4% of the Moroccan GNP, 22% of the total value of imports, and six times the total development aid paid to Morocco (de Haas 2005). In 2007, the International Organization of Migration (IOM) assessed the amount of remittances from the three million Moroccan migrants at $ 4.31 billion. Refass estimates the actual amount of remittances to be at least one-quarter to one-third higher, since money is also sent through informal channels and/or in the form of goods (Refass 1999). According to Troin, international migration is essential for the Moroccan economy (Troin 2006).

Although the focus of interest often lies on international migration, national labor migration must not be neglected. Kerzazi estimated the number of national migrants in the 1990s at 4.2 million (Kerzazi 2003); more recent data, however, are not available.

I-8.1.2.4 Resource Management

In the rural areas of the provinces of Ouarzazate and Zagora, agriculture and livestock breeding are still prominent sources of livelihood security. In the oases of the Drâa catchment, people cope with temporal water scarcity in many different ways. Due to permanent cultivation and commonly acknowledged water and land rights in the oasis, the management of irrigated fields follows well-established patterns, which are regulated by the village communities.

Depending on the environmental setting and the social structure within a village, water can be "owned" and distributed according to two complementary water-rights systems: the *mulk*-system, and the *allam* or *afalys*-system, as it was called in the pilot-community of Tichki in the High Altas Mountains. Under the *allam*-system, water rights are tied to the ownership of specific plots of land. Land can only be sold or inherited with the associated water rights. Irrigation depends on the location of a field and the demand of the crop. Fields are irrigated in sequence, regardless of the owner of the field. The duration of an irrigation cycle depends on water availability and the number of fields in the system. The *allam/afalys*-system is used if water resources are sufficient. Arrangements between upper- and downstream riparian owners are also necessary.

Under the *mulk*-system, water rights are independent of rights over land. Water and land can be given away, sold or inherited independently. Families or individuals own parts of the irrigation canals and the right to use irrigation water during fixed periods of time (*nouba*). During these times, the farmer is entitled to irrigate his fields, regardless of the position of his field. The *nouba*-system is used to manage scarce and contested resources. These systems are fully functional only in the mountainous regions in northern parts of the Drâa catchment. Due to a series of dry years, the water outlets from the Mansour Eddahbi Dam near Ouarzazate were erratic and insufficient to allow a functioning nouba irrigation system in the Middle Drâa valley. Nevertheless, the knowledge of the systems is accessible and could be revitalized if enough water becomes available.

Another effect of the recent water scarcity and the deteriorating economic situation in rural areas is the fact that migrants' remittances have become principal sources of income in many regions in Southern Morocco that influence agricultural options and the pastoral strategies of transhumant herders.

Traditional and state institutions – parallel structures and conflicting decisions

Pastures and arable lands are the key resources in rural Southern Morocco. In contrast to the privately owned irrigated lands, pastures and the communal land (*agdal n'igram*) are – in theory – owned and managed by local tribal institutions, who traditionally set the rules for access and use. In practice, the use of collectively

owned natural resources is variable, and often disputed between conflicting groups. These decision-makers represent overlapping territorial and juridical units such as 'community territories' or 'tribal land', which have entirely different political and judicial backgrounds.

The administration of natural resources has been contested since Morocco was a French protectorate (1912-1956). The division of Morocco into a northern 'Useful Morocco' (*Le Maroc utile*) and the Southern 'Necessary' or 'Useless' Morocco" (*Maroc inutile*) by the French general Lyautey had serious consequences for administration and development of many regions (Müller-Hohenstein and Popp 1990; Pennell 2000). The expropriation of land, common in the fertile northern plains or in the Middle Atlas, was insignificant in the south. Much of the scarce, arable land in the oases and the rangelands remained untouched. On the other hand, no efforts were made to develop the south. Agricultural and infrastructural development projects were concentrated in the north, and economically important trade routes between the south and the north were closed.

After independence in 1956, the central government claimed the right to manage common lands via central agencies such as the forest service (*Eaux et Forêts*) or modern territorial bodies like the rural communities (*Communes rurales*) founded in 1958. A *Qaid*, appointed by the Ministry of Interior in Rabat, presided over the municipal council. Previously a *Qaid* was a tribal leader, who later became "a member of the Moroccan political and bureaucratic elite, a trained administrative official" (Hart 1984), established to weaken the institution of the tribal assembly (ar. *jmaa*) and to shift processes of decision-making to the new communities an effort that was not successful. In spite of the formal responsibility of governmental authorities, public confidence and acceptance often lies with tribal institutions and their management rules. Decision-making regarding common land is still generally considered as a tribal issue, even though tribal institutions are not formalized or may be inoperable in many cases (Kirscht and Finckh 2008).

In Southern Morocco, communal boundaries are not consistent with tribal territories. Tribal territories can touch more than one rural community, while the same community could encompass more than one tribal territory. Therefore, tribal decisions related to rangelands or other common resources go beyond the boundary of a *commune rurale* where the user village is located. Due to overlapping structures of modern administrative and local tribal territories, decisions regarding common lands are made by actors of different legitimacies, and may affect the acceptance of management decisions.

I-8.1.2.5 Conclusions

Our description of the societal developments in Southern Morocco shows the interrelationship of historically based economic, social, and cultural patterns with the current economic and political situation. Southern Morocco has always been an

area with high mobility. Historically the region attracted migrants because of its function as a gate to the trans-Saharan trade routes. The descendants of the various Arab groups who entered the region over the centuries were, until very recently, important actors in the political and economic arenas of the Middle Drâa valley. Their relationship with the historically defeated local sedentary population is still marked by a hierarchical relationship and status differences. The more segregated northern part of the Drâa catchment, especially the mountainous areas, were less affected by Arab influences. To date, the population is predominant Berber. Even the colonial expansion could not destroy the tendencies toward segmentation and the historically acephalous socio-political structure of the Berber society.

In addition to the radical changes during the colonial and postcolonial period, some of the social, political, and cultural patterns of the pre-colonial times remain intact and influence current political decisions and conflicts, at least on local levels. This includes decision-making processes related to natural resource management influenced by climatic variability and other natural processes, historically and culturally prescribed customs, as well as by the demands of modern living conditions.

Today the Drâa catchment is characterized by a massive emigration of mostly young men to the economic centers of the north and a strong growth of the regional urban settlements. The demography of the provinces of Ouarzazate and Zagora is already characterized by low population density, compared to the prospering regions in the northwest of Morocco. This disparity is likely to increase because the rural population growth will remain slow and only the already urbanized centers will expand.

Although agriculture and livestock breeding are still the principal activities of the rural population, livelihood security depends on income generated by migrants. In fact, this is one of the most important income-generating strategies of the rural population. In almost every household in the Drâa valley, one or more family members migrated and contribute parts of their income to their households at home. National and international migration and the related processes of urbanization influence the socio-economic development and the demographic change in our working area.

References

Courbage Y (1995) Fertility transition in the Mashriq and the Maghrib: education, emigration, and the diffusion of ideas. In: Obermeyer CM (ed) Family, Gender, and Population in the Middle East Policies in Context, pp. 57-79. American University in Cairo Press, Cairo

de Haas HG (2003) Migration and development in Southern Morocco. The disparate socio-economic impacts of out-migration on the Todgha Oasis Valley. OPTIMA, Rotterdam

de Haas HG (2005) Morocco: From emigration country to Africa's migration passage to Europe. Country profile Morocco. Migration Information Source, October 2005. http://www.migrationinformation.org/Profiles/ display.cfm?ID=339. Accessed January 2010

Direction de la Statistique (1995) Population Légale du Royaume d'après le Recensement Général de la Population et de l'Habitat (Septembre 1994). Rabat

El Moudden A (2002) Histoire. In: Ragala R, Refass M (eds) Atlas du Maroc, pp. 24-27. Editions JA, Paris

Hart D (1984) The Ait Atta of Southern Morocco. Middle East & North African Studies Press, Cambridge

Haut Commissariat au Plan (2005) Recensement Général de la Population et de l'Habitat 2004. Centre de Lecture Automatique de Documents, Rabat

Kerzazi M (2003) Migration rurale et développement au Maroc. Faculté des lettres et des sciences humaines Université Mohamed V, Rabat

Kirscht H, Finckh M (2008) The Incongruity of Territorial Perceptions as an Obstacle to Resource Management in Communal Land – Southern Morocco. Mt Forum Bull 8(2):11-13

Müller-Hohenstein K, Popp H (1990) Marokko. Ein islamisches Entwicklungsland mit kolonialer Vergangenheit. Klett, Stuttgart

Obdeijn H (1993) Op Wek naer werk ver van Huis: Marokkaanse Emigratie in historisch perspectif. Migrantenstudies 9(4):34-47

Pennell CR (2000) Morocco since 1830: a history. C Hurst & Co, London

Platt S (2008) Development of the Urbanized Regions in the Provinces of Ouarzazate and Zagora until 2020. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007, 3rd edn., pp 61-62. Department of Geography, University of Bonn, Bonn

Policy Project, The Futures Group International (1997) SPECTRUM. Policy Modeling System. Washington. http://www.policyproject.com/software.cfm?page=Software&ID=Spectrum. Accessed 19 January 2010

Ragala R (2002) Population. In: Ragala R, Refass M (eds) Atlas du Maroc, pp. 30-34. Editions J.A., Paris

Refass M (1999) Les Transferts des Ressortissants Marocains à l'Etranger. In: Berriane M, Popp H (eds) Migrations Internationales entre le Maghreb et l'Europe, pp. 97-105. LIS Verlag, Passau

Stover J, Kirmeyer S (2005) DemProj 4: A Computer Program for Making Population Projections. Washington. http://data.unaids.org/pub/Manual/2007/demproj_2007_en.pdf. Accessed 19 January 2010

Troin JF (2006) Maroc: les multiples visages d'un État contrasté. In: Troin JF, Bisson J, Bisson V, Brûlé JC, Escallier R, Fontaine J, Signoles P (eds) Le Grand Maghreb, pp. 211-236. A. Colin, Paris

Zainabi A (2003) La Vallée du Dra: Développement Alternatif et Action Communautaire. http://siteresources.worldbank.org/DEC/Resources/16678_Zainabi.pdf. Accessed 19 January 2010

I-8.2 Economics of agriculture and water use

A. Kuhn

The aim of this section is to describe the role of economics in water-related interdisciplinary research. The fundamental assumption is that decisions on resource use are based on economic considerations. Economic behavior related to natural resource use is driven by natural limitations such as ecological processes and resource endowment, the need of growing populations to earn a living from resource-based activities, and the availability of production technologies and management options. It is also important to account for the preferences of individuals and groups regarding occupations, consumption of food and other products of land use, and collective or administrative rules and restrictions regarding land and water use.

As already elaborated in preceding chapters, Morocco and Benin differ significantly in their specific water resource problems. Morocco, as a semi-arid country, is more directly affected by water scarcity, especially since water is a decisive production input in its agricultural sector and subject to comprehensive management. In Benin, by contrast, the availability of water from renewable sources per capita is much more favorable. The annual precipitation levels and patterns allow for rainfed crop growth, with irrigation agriculture only playing a marginal role. Active water use is largely restricted to household purposes and livestock husbandry. For that reason, the analytical approaches and simulation models used to model the two countries differ substantially. While in Morocco a planning model for water use comprising the Drâa river basin was chosen, the focus in Benin was on agricultural land use, which is dependent on rainfall and, through changing vegetation cover, provides human feedback into the water cycle, albeit not in a direct fashion. This chapter illustrates specific problems of resource management in the two countries from an economic perspective and introduces the different economic modeling approaches that were applied for simulations, projections, and analyses of resource management approaches and policies.

I-8.2.1 Climate and socio-economic impacts on Benin's agriculture

A. Kuhn and I. Gruber

Abstract

Agriculture plays an important role in Benin's economy as the most important source of income. Productivity growth is generally low, which raises questions about the future food supply situation if the population continues to grow at current rates. With an annual growth rate of 2.8%, Benin's population will double within 26 years, and as the major part of the economically active population is still earning its income from agriculture, population growth exerts pressure on available land resources. This subsection discusses the most important links between agricultural land use and the water cycle. Beninese farmers have scarcely begun to take an active role in managing parts of the water cycle. However, evolving land scarcity following population growth, or insufficient reliability of the onset and end of rainy seasons as a consequence of Climate Change, might induce investment into supplemental irrigation technologies. Nevertheless, links between agriculture and the water cycle in Benin significantly influence rural economics through possible land use patterns, the provision of food to the population, the survival of traditional production modes such as transhumance, and the regional climate itself via feedback mechanisms.

Keywords: Farming systems, shifting cultivation, farm-household models, bio-economic modeling

I-8.2.1.1 Introduction

Agriculture plays an important role in Benin's economy as the most important source of income: about 65% of the workforce are employed full- or part-time in agriculture, according to UNDP (2004). However, productivity growth is generally low, which raises questions about the future food supply situation if the population continues to grow at current rates. With an annual growth rate of 2.8%, Benin's population will double within 26 years, and as the major part of the economically active population is still earning its income from agriculture, population growth exerts pressure on available land resources. Even though the overall

nutritional status of the population today seems to be satisfactory, a significant proportion, especially children and women in poor families, are threatened by protein malnutrition and insufficient energy intake. Food shortages occur sporadically before the harvesting season, a time when stocks are running low. Even though the production of food crops has been considerably expanded due to high demand caused by the high population growth, most of this increased food production is not a result of intensification on the existing agricultural area, but almost exclusively of expanding cropland. New and sometimes marginal land is taken under cultivation, and the fallow period is shortened in order to meet the higher demand. In the southern regions of Benin where the majority of the population lives, scarcity of cropland is already a major problem, leading to internal migration northwards into Central Benin.

I-8.2.1.2 Land use, agriculture, and food security

Agricultural land use occupies a swiftly increasing share of Benin's total land area. Agricultural land use increased from 20.5% of total land area in 1990 to 31.8% in 2007,[1] meaning that the expansion of farmland almost kept pace with the total population growth. Much of Benin's agriculture is still characterized by shifting cultivation, where four to eight years of crop cultivation are followed by a fallow period of roughly the same duration. Another important element of the agricultural conditions is the annual cycle of rainy and dry seasons, whereby rain fed cultivation is confined to the rainy season. While the sustainability of shifting cultivation is threatened by rapid population growth, leading to ever more pressure on available land resources, meteorological scenarios predict that Climate Change is likely to shorten the rainy season and to prolong the duration of dry spells within the rainy season (Paeth et al. 2009), increasing the risk to farmers and depressing average yields.

Benin covers a total area of 112,620 km² inhabited by slightly more than 6.7 million people, resulting in a population density of 57 inhabitants per square kilometer on average, but with large regional differences. With about 240 people per km² in the southern part of the country, more than half of the total population lives in 10% of the country's area, whereas in the north, there are fewer than 25 people per square kilometer. Due to the high population growth, almost 2.8% annually, the total population is expected to exceed 10 million in 2016 (FAO 2003). As the southern regions are already struggling with land scarcity, internal migration to less land-scarce areas, particularly in the central departments, could be observed in recent years. In these latter regions (mainly the departments Collines, Donga, and Borgou) more and more land is taken into cultivation, obviously expanding the cultivated agricultural area at the expense of forests, bush savannah,

[1] FAOSTAT Online Database (http://faostat.fao.org/site/377/default.aspx#ancor)

and long-term fallow. Admittedly, exact land use figures are difficult to obtain as land registration and statistical monitoring are still being developed, while parallel systems of old and new land use rights still coexist (see sect. II-4.4). The *Direction des Forêts et des Ressources Naturelles* (2002) estimates regional land use in Benin as illustrated in table I-8.2.1. The largest share of the land use is occupied by rain-fed cultivation of annual crops such as maize, cassava, yams, sorghum, millet, and cotton. 'Pastures' account for another large proportion of the agricultural area, and essentially represent the available reserves for additional cropland in Benin. Pastures subsume a broad variety of vegetation cover, ranging from shrubs to (non-protected) forests.[2] Permanent crops, such as oil palms, cashews, or mangoes, are gaining in importance in some regions, while irrigated crops, predominantly rice, are of minor significance.

Table I-8.2.1: Regional differences in land use in Benin [in 1000 hectares] (Source: CENATEL 2002).

Department	Population density [cap/km²]	Rainfed cultivation	Irrig. and permanent crops	Pastures	Pastures as % of agric. land[a]	Conservation areas	Water settlements
Atlantique	272.2	236.7	20.8	15.9	5.8	-	21.1
Mono	263.9	101.9	8.1	15.4	12.3	-	11.0
Plateau	120.7	240.9	7.9	40.1	13.9	43.1	5.2
Couffo	225.0	187.9	0.0	40.6	17.8	-	4.6
Oueme	164.9[b]	63.2	6.6	18.8	21.2	-	17.7
Zou	118.1	302.1	7.1	185.8	37.5	-	13.2
Collines	44.5	639.7	3.6	409.0	38.9	130.7	20.6
Alibori	20.2	709.9	-	610.7	46.2	1,240.7	11.7
Atacora	26.1	706.1	0.6	781.6	52.5	600.3	13.4
Borgou	27.3	843.1	1.6	1,362.8	61.7	427.5	16.4
Donga	24.1	365.7	0.4	781.6	68.1	297.6	6.4
Benin tot.[c]	47.7	4,397.4	113.6	4,262.3	48.6	2,739.9	296.4
in %	-	37.9	1.0	36.7	-	23.6	2.6

[a] 'Agricultural land' is defined as the sum of all cropping area types and pasture.
[b] without Porto-Novo and the urban agglomeration of Porto-Novo
[c] without Littoral and Porto-Novo

[2] Protected forests are accounted for under 'conservation area' in table I-8.2.1.

Given that shifting cultivation is still the dominant farming system, it is reasonable to assume that 'pasture' is largely identical with fallow land. This is strongly supported by the fact that the share of pasture across Benin's *départements* decreases with increasing regional population density (see table I-8.2.1). Fallow land fulfils several functions within the system of shifting cultivation, the most crucial of which is to restore soil fertility after a cropping cycle. Moreover, as forage cultivation is practically non-existent in Benin, natural pastures are almost the sole source of fodder for livestock. These natural pastures are often community land, allowing all persons the use of the area. If the agricultural area is expanding, the pasture area, and thus the availability of forage, is being reduced. The interrelation between agricultural land and pasture areas, and the formation of new crop fields in particular leads regularly to conflicts between farmers and livestock herders.

Moreover, fallow land, provided that it has not been cultivated for ten or more years, may often be classified as forest (see sect. I-7). Forests are economically relevant as a source of timber, firewood, and fruits, but their exploitation is not regulated by a strong framework of property rights. Thus, increasing demand for cropland by peasant farmers leads to high rates of deforestation. The expansion of agricultural land usually accompanies progressively reduced vegetation cover, which often means deforestation and the conversion of tree savannah into shrub/grass savannah or bare land.[3] Currently, forests cover 21.3% (2.35 million ha) of the total area in Benin, while at the beginning of the nineties this figure was still at 30% (World Bank 2008). Between 1990 and 2000, Benin's total deforestation rate was 2.1%, and it is estimated that this rate has increased to 2.5% since 2000.[4] The 'battle against deforestation' is considered an important goal by the government,[5] but even though numerous donor projects are trying to inform and sensitize rural inhabitants about the relevance of forests and to support reforestation, few successes are visible, as demand for crop land usually trumps conservation efforts.

Since Benin is a low-income country, there are few alternative sources of income for large parts of the rural population beyond subsistence farming. High marketing costs tend to depress revenues from surplus production, while at the same time pushing up the costs of fertilizers and other inputs. Together with the lack of access to credit, these circumstances result in slow area productivity improvements, which are not nearly sufficient to keep pace with population growth. Available land reserves and cheap labor are more or less the only significant factors of production used by the average farm household. Only when land reserves are approaching exhaustion, as it is the case in southern Benin, does the use of fertilizer begin to make sense economically. According to data from the FAO database, an average annual nitrogen consumption of 21,000 tons from 1998 to 2002 translates into a mere 4.7 kg per ha of cultivated area, which is not sufficient to offset the worsening land per capita ratio as illustrated in figure I-8.2.1.

[3] Source : http://www.uni-hohenheim.de/~atlas308/a_overview/a3_1/html/english/a31ntext.htm

[4] Source: http://rainforests.mongabay.com/deforestation/2000/Benin.htm

[5] Source: http://www.un.org/esa/agenda21/natlinfo/countr/benin/natur.htm#forests

The use of arable land (i.e. cropland under annual crops) per capita in Benin declined from than 0.42 ha per capita to 0.32 ha per capita in 2006. The end of state socialism and the cotton boom during the nineties increased the profitability of farming, thus accelerating the conversion of savanna and forest into cropland. This made Benin's arable land per capita decrease less than the average of West African countries. Nevertheless, if the development of crop productivity continues at its current slow pace, land scarcity may eventually require changes in the crop mix towards crops with higher calorie yields per hectare such as cassava.

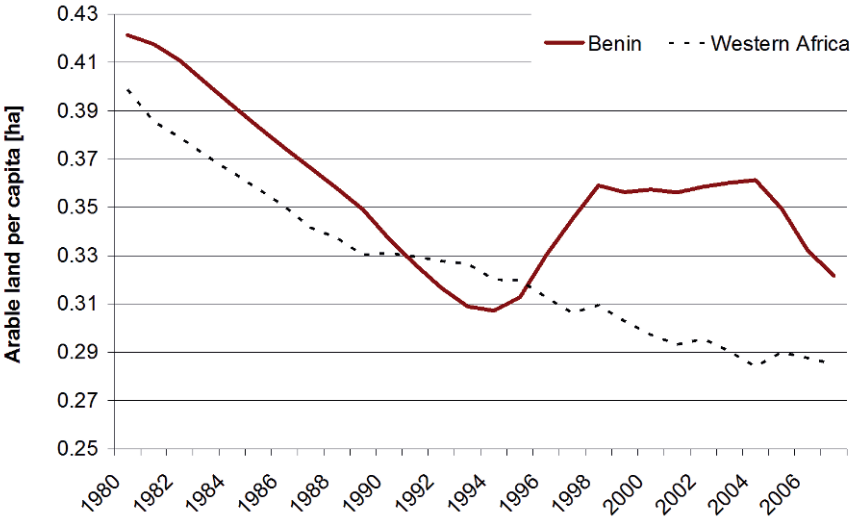

Fig. I-8.2.1: Arable land per capita for Benin and West Africa (Source: FAOSTAT Online Database 2009).

I-8.2.1.3 Simulation of cropland use trends in Benin

The major task of agricultural and resource economics within the IMPETUS project was to develop a numeric model for forecasting the future amount of land used for agricultural purposes. Changes in land use lead to about substantial changes in vegetation cover, which, in turn, is an important driver of regional Climate Change (see sect. I-5.1). Simulating future trends in land use changes, however, is a complex task due to the various interactions of biophysical, agronomic, and economic processes that have to be taken into account. Thus, such a model should base future predictions as far as possible on dynamically formulated economic processes, and as little as possible on exogenously imposed trends in certain driving forces. Most importantly, existing knowledge on the economics of subsistence

farming under population pressure with limited, degradable land resources should be considered as much as possible. The macroeconomic role of the agricultural sector should also be given due consideration, as changes in the agricultural sector in agrarian economies have far-reaching consequences for incomes, wages and the potential to compensate domestic shortfalls in agricultural supply with food imports. The resulting simulation model will produce projections on future land use, crop and livestock production, and food security.

As already mentioned above, the interaction among renewable resources, ecosystems, and resource users has been extensively analyzed in recent decades. Based on theoretical work begun by Chayanov (1966)[6], and later continued by Boserup (1965), and Binswanger and Rosenzweig (1986), and others, a new class of bio-economic models has emerged addressing the interaction of subsistence agriculture and natural resource management for developing countries (Holden and Shiferaw 2004). These numerical simulation models are mainly based on linear or non-linear mathematical programming methods to simulate individual farms or aggregate farm sectors within regional economies (Hazell and Norton 1985; Janssen and Van Ittersum 2007). The distinctive feature of bio-economic models is that they capture the mutual feedback processes of human decisions and natural processes by incorporating endogenous productivity functions for natural resources, i.e., the impact of management decisions (e.g., use of fertilizer, conservation measures) on agronomic and ecological processes (e.g., yield response, but also processes such as formation of organic matter in soils), but also the impact of changes in resource productivity due to ecological processes (e.g., degradation) on management decisions, for instance a switch to more extensive production modes (e.g., use of fertilizer, conservation measures), thus capturing the feedback processes of human decisions and natural processes. Barbier and Bergeron (2001) use a recursive-dynamic model for a small river basin in Honduras with a five-year planning horizon. The resource endowment in this model comprises labor, livestock, trees, land of different quality, and ploughs as machine capital. As a biophysical component, the yield response is simulated using the EPIC-model. Barbier and Hazell (2000) concentrate on the interaction between croppers and transhumant herders in a village in Niger, and take the effect of drought risk on farmers' decisions explicitly into account. Here, the productivity of fallow land and savannahs as pasture for livestock is modeled as a function of grazing intensity complementing the endogenous productivity of the cropland. Similar models have been used by Okomu et al. (2004), and Holden and Shiferaw (2004). Aspects of decline and collapse are dealt with by researchers investigating so-called ‘poverty traps’ using bio-economic simulation models (see Barrett 2003), as the interaction of resource degradation and human development can take completely different paths. All of these bio-economic modeling approaches are confined to relatively small areas (vil-

[6] The Russian rural sociologist and agricultural economist Alexandr Chayanov published his seminal work ‘On the theory of the peasant economy’ under Soviet rule in the 1920s. It was among the first more rigorous analyses on the economics of subsistence farming. Its publication in English – only in 1966 – made it available to the wider community of development economists.

lages, small regions, river basins), implying that prices for products and labor are usually exogenous, even though many of the determinants of resource use are closely related to labor markets and the net trade position of farm households.

The quantitative approach presented in this section uses elements of resource use modeling from bio-economic models on a larger scale. The simulation model BenIMPACT (Benin Integrated Modeling System for Policy Analysis, Climate and Technology Change) is a spatial agricultural sector model covering all regions of Benin. Trade with neighboring countries and the world market is also included in the model. In accordance with the regional focus of IMPETUS, the spatial resolution of BenIMPACT is highest in the Upper Ouémé basin. For that purpose, the *départements* Borgou, Collines, and Donga were disaggregated to the *commune* level, whereas all other regions are represented on the level of the *départements*. BenIMPACT includes strong elements of farm-household models, as it comprises both supply and demand for agricultural commodities. The main characteristic feature of a farm-household model is that production and consumption decisions are made simultaneously, for instance by assuming that one person is responsible for both areas (Bardhan 1999). Crop and livestock products are supplied by regional aggregate farm models with a calibrated profit function.[7] These representative farms are assumed to maximize their profits by deciding on the use of land, crop mix, on-farm and off-farm labor, and fertilizer. Food consumption by rural households is determined by commodity prices and household income, which is, in turn, generated to a significant degree by farming activities, depending on the income structure of the population in a particular region.[8]

A detailed description of the most important features of BenIMPACT can be found in Jansson (2005a; 2005b; 2005c) and Gruber (2008). While in previous versions of BenIMPACT (up to the year 2005), supply and demand were solved separately in an iterative procedure, the two modules have been integrated recently into a simultaneous model as a mixed complementary problem (MCP) by deriving the objective function. As to the spatial dimension of BenIMPACT, Benin is divided into twenty-eight regional units, with a focus on the Upper Ouemé basin. In addition, the neighboring countries of Benin are represented by stylized supply and demand functions. Even though the model captures the whole country, decision-making in agricultural production occurs at the level of the farm-household model where production influences income, which, in turn, determines consumption. The entire causal network embodied in BenIMPACT is illustrated in figure I-8.2.2.

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[7] More precisely, the quadratic profit function is calibrated to observed crop mix shares instead of absolute areas, using the method of Positive Mathematical Programming (PMP; Howitt 1995). In contrast to standard models using PMP, this approach avoids the necessity of shifting the supply functions of individual crops into a hypothetic future situation.

[8] Technically, commodity demand is represented by a Generalised Leontieff expenditure system (Diewert and Wales 1987; Ryan and Wales 1996) with time separability. This means that products consumed in different time periods are considered as different goods, with no cross price effects except via annual income.

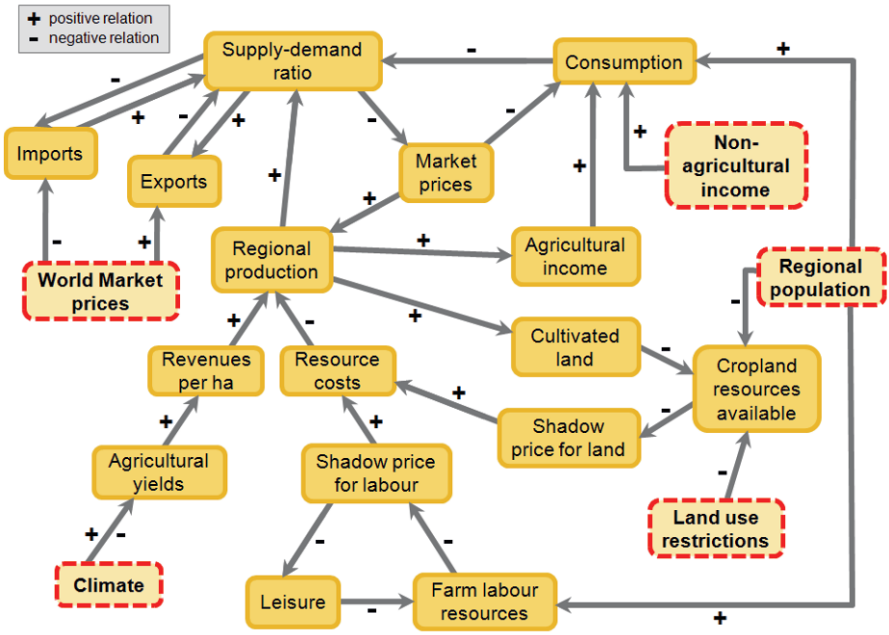

Fig. I-8.2.2: Network of causal processes in BenIMPACT.

Aggregate farming units represent production in each model region on the basis of national and regional statistics as well as their own data collection of production costs, each representing the production, consumption and trade of all farm households in the department. Each year is divided into four periods in order to capture the differences between the rainy and dry seasons as well as the multiple harvest seasons per year of certain crops. Eight major important food and cash crops are currently included in the model, plus five livestock commodities[9]. The costs of the commodity supply comprise transport costs, storage costs, costs for input use in farming, as well as costs for labor and shadow prices for land once the available land is used up. The inclusion of explicit trade and storage costs implies that regional and seasonal prices differ by fixed price spans provided that trade takes place.

The model is calibrated in order to replicate the average of the years 2001 and 2002 (called 'base year' further on), while further scenarios are calculated in a recursive-dynamic fashion in five-year steps until 2025. For the base year, production is computed using statistics from national agricultural organizations, disaggregated into time periods using a crop production calendar together with precipitation data. The demand is computed from data on regional per capita consumption of food crops, seasonally adjusted using observed variations in prices and the

[9] These are maize, cassava, yam, pulses, cotton, sorghum and millet, peanuts, and rice.

elasticities entering the demand system calibration. Trade and storage costs are estimated by minimizing the deviations of costs from an assumed trade cost function and of prices from observed prices, respecting the market balance and arbitrage conditions (Jansson 2005a).

The impact of regional Climate Change can be transmitted to BenIMPACT via the expected changes in base crop yields. Moreover, Climate Change will also affect the natural vegetation that represents the fodder basis for livestock husbandry in Benin. To take into account the effect of the use of fertilizer on crop yields, a flexible yield function is part of the model. The current version also employs a wage function, which depresses the regional wage level in the non-agricultural sector when off-farm labor, i.e. the labor supply, increases. This flexibility of the wage rate is indispensable, as agriculture is still the most important employer in rural areas of Benin, and therefore changes in population density and non-agricultural employment have immediate repercussions on the local labor market.

I-8.2.1.4 The role of livestock husbandry in the water cycle

Direct agricultural water demand is to a large part generated in the livestock sector, as animals have to be watered. The current situation of livestock husbandry in Benin is characterized by extensive production methods. The capital used is limited largely to the animals themselves, while the labor input is small compared to that of farming. However, the transhumant production modes common for small and large ruminants are particularly dependent on sufficient availability of land, particularly savannah, forest, and grazing opportunities on harvested crop fields. Thus, this extensive production mode is largely based on and constrained by the availability of the natural resources of water and pasture to livestock keepers. Productivity in livestock management is generally low, accompanied by a multi-purpose motivation for keeping livestock. Therefore, the ability to adapt to changed external conditions is often limited due to liquidity constraints, and also because the motivation for keeping livestock is broader than the generation of ‘profits’. Since the herds are the only tangible capital of livestock keepers, maintaining these capital endowments requires a constant and adequate availability of the resources of water and natural pasture. Both resources are directly influenced by climatic conditions, which is why Climate Change is seen as an important driving force for livestock development.

In order to show the relevance of resource availability, we look at the regional water demand of livestock. In the south, the total amount of water required to sustain the existing livestock herds is less than 20% of the total human water needs, when assuming 20 liters per person per day in 2002. In the northern departments of Borgou and Atacora, animals’ water consumption slightly exceeds human demand, and livestock herds in Alibori consume twice as much as the human population (Gruber et al. 2009). Currently the ratio of water needs of livestock to water

needs of humans is shifting upwards because the livestock population has grown faster than the human population.

Livestock production depends on water for two reasons: first, as animals have to be watered, regional rainfall patterns determine the spatial and temporal distribution of livestock directly by recharging available drinking water sources. Second, livestock husbandry is indirectly determined through natural forage production caused by precipitation. The forage productivity in regions with low precipitation and, therefore, a lower availability of natural forage like pasture or forest, is a function of rainfall (Fafchamps and Gavian 1996).

Different traditional strategies exist to deal with seasonal shortages of natural input factors (water and pasture). One strategy to deal with scarcity of input factors is variation in the use of water sources depending on season and region. Animal keepers use the nearest water sources first, and the more distant ones afterwards. The same strategy, i.e. using the nearest fodder source first, is applied for feeding. Several sources of forage, such as natural pasture, cuts from trees, or harvest residues are used, whereas the cultivation of fodder crops is still marginal. Another obvious strategy of dealing with scarcity in natural resources is transhumance, i.e., the seasonal migration of livestock following the supply of both forage and water. But these strategies can only be applied on a limited scale and only as long as sufficient land is available.

Land availability is the aspect where the second driving force, human population growth (see fig. I-8.2.3), exerts its dominating influence on livestock husbandry. Due to the combination of high population growth and stagnating crop yields, farmers expand production by converting savannah and fallow into agricul-

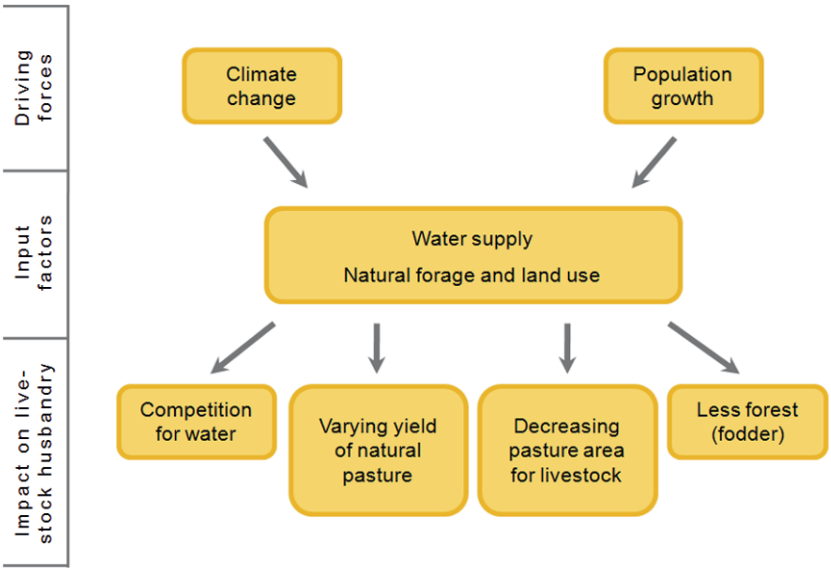

Fig. I-8.2.3: Influence of driving forces on resources.

tural land. As livestock production depends to a great extent on the availability of natural pasture, the expansion of cropland leads to a reduction of natural pasture, reducing the availability of forage.

Moreover, forest is also converted to cropland to a larger extent. Not only does the current deforestation rate of 2.2% per annum (UNEP 2007) influence the general ecological system, but also the livestock management. As tree cuttings are an essential part of the forage for ruminants during the dry season, the reduction of forests also leads to less fodder threatening the current production system.

To analyze numerically the impact of the two driving forces – Climate Change and population growth – on livestock management, and to take the interactions of livestock keeping and cropping into account, a livestock module was included into the agricultural sector model BenIMPACT. Agricultural activities in livestock husbandry include the keeping of cattle, sheep, goats, pigs, and chickens. The model commodities related to livestock husbandry are beef, mutton, goat meat, pork, and chicken meat. As seen before, livestock keeping in Benin is characterized by extensive production methods, which is why only the major input factors such as land including forage availability, labor, and water, are included into the model. The input factor of land for grazing of ruminants, including fodder availability, is restricting extensive ruminant husbandry in two ways. First, it is assumed that crop farmers have stronger property rights to land, which means a bundle of rights to claim and cultivate land. Extensive livestock keepers, however, usually do not possess land titles and may only use the remaining land for their livestock husbandry. The natural productivity of these remaining land resources then determines the maximum number of livestock in a region: The sum of available fodder resources has to be greater than or equal to the feed requirements of the ruminants kept.

In order to capture the climatic drivers for the availability of biomass, a biophysical component was added to the BenIMPACT simulation model. To calculate the quantity of available forage and the seasonal trends of natural pasture, the model CROPWAT is used. Normally, CROPWAT is applied for calculating evapotranspiration, crop water use, irrigation, or assessments of rain fed agriculture (Allen et al. 1998). For this study, the CROPWAT model was modified and adjusted with respect to different regional parameters. Therefore, in the livestock module of BenIMPACT CROPWAT is able to calculate the changes of natural forage and forests due to climatic variations in Benin.

Herd sizes in the extensive livestock sector (the ‘activity levels’ of the sector) are determined by an iso-elastic supply function with low supply elasticities, and by exogenous growth factors. The growth factors are the population growth for non-ruminants and the rates of birth and mortality for ruminants. The growth rates of ruminants are regionally corrected by the fodder restriction. If the fodder availability is insufficient in a region and the livestock's needs cannot be fulfilled in a model period, regional and seasonal reduction coefficients are calculated. These coefficients reduce the number of ruminants to a level where the fodder restrictions can be fulfilled.

I-8.2.1.5 Conclusions

This subsection discussed the most important links between agricultural land use and the water cycle. As opposed to a country like Morocco, where these links are very direct (see next subsection), Beninese farmers have scarcely begun actively managing parts of the water cycle. Evolving land scarcity following population growth, or insufficient reliability of the onset and end of rainy seasons as a consequence of Climate Change might, however, induce investment into supplemental irrigation technologies. Nevertheless, the links between agriculture and the water cycle in Benin significantly influence rural economics through possible land use patterns, the provision of food to the population, the survival of traditional production modes such as transhumance, and the regional climate itself via feedback mechanisms. The simulation model BenIMPACT was developed to obtain an idea about the importance and magnitude of these links. Selected results of the simulations and scenarios for Benin's agricultural sector can be found in section II-4.1 in the second part of this book.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome

Barbier B, Bergeron G (2001) Natural Resource Management in the Hillsides of Honduras: Bioeconomic Modeling at the Microwatershed Level. Research Report 123. IFPRI, Washington DC

Bardhan P, Udry C (1999) Development Microeconomics. Oxford University Press, Oxford

Binswanger H, Rosenzweig MR (1986) Behavioral and Material Determinants of Production Relations in Agriculture. J Dev Stud 22:503-539

Boserup E (1965) The conditions of agricultural growth. The economics of agrarian change under population pressure. Earthscan Publications Ltd., London

Chayanov AV (1986) The Theory of Peasant Economy. University of Wisconsin Press, Madison, WI

Diewert WE, Wales TJ (1987) Flexible functional forms and global curvature conditions. Econometrica 55:43-68

Fafchamps M, Gavian S (1996) The Spatial Integration of Livestock Markets in Niger. J Afr Econ 5(3):366-405

FAO (2003) FAO: Aperçus Nutritionnels par Pays – Bénin. FAO, Rome

Gruber I (2008) The impact of socio-economic development and climate change on livestock management in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2008/gruber_ina/1388.pdf. Accessed 23 Oct 2009

Gruber I, Kloos J, Schopp M (2009) Seasonal water demand in Benin's agriculture. J Environ Manage 90(1):196-205

Howitt RE (1995) Positive Mathematical Programming. Am J Agr Econ 77(2):329-342

Jansson T (2005a) Two ways of estimating a transport model. Agricultural and Resource Economics. Discussion Paper 2005 (1), Institute for Agricultural Policy, Market Research and Economic Sociology, University of Bonn, Bonn. http://www.ilr1.uni-bonn.de/agpo/publ/dispap/download/dispap05_01.pdf. Accessed 10 November 2009

Jansson T (2005b) A demand system for the BenIMPACT model. Technical Paper, March 2005, Department for Economic and Agricultural Policy, Bonn University, Bonn. http://www.ilr1.uni-bonn.de/agpo/rsrch/impetus/doc/tecpap-demand-2005.pdf. Accessed 10 November 2009

Jansson T (2005c) The Economic Model BenImpact. Technical Paper, May 2005, Department for Economic and Agricultural Policy, Bonn University, Bonn. http://www.ilr1.uni-bonn.de/agpo/rsrch/impetus/doc/tecpap-overview-2005.pdf. Accessed 10 November 2009

Ryan DL, Wales TJ (1996) Flexible and semiflexible consumer demands with quadratic Engel curves. Discussion paper 96-30. University of British Columbia, Vancouver

UNDP (2004) Human Development Report 2004: Cultural Liberty in Today's Diverse World. UNDP, New York

UNEP (2007) Forests, Grasslands and Drylands: Country Profile Benin. http://countryprofiles.unep.org

World Bank (2008) World Development Indicators Database. World Bank, Washington DC

I-8.2.2 Hydro-economic processes and institutions in Southern Morocco

C. Heidecke, A. Kuhn, and C. Liebelt

Abstract

Hydro-economic interactions in Morocco are analyzed herein, with a special focus on the relationships between irrigation water and agricultural production in the Middle Drâa valley. An integrated analysis of the river basin level in the Drâa valley is necessary to understand the processes and interactions of water and agriculture. Any analysis has to account for the institutional arrangements governing access of farm households to irrigation water, as well its distribution among villages and oases. Moreover, hydrological aspects need to be combined with agricultural production characteristics (crop patterns and technologies used), as farmers are still by far the most important water consumers in the region. Domestic water use should be represented within an integrated analysis, as it is of the highest priority and is likely to increase in the future. As water markets have not yet emerged and water distribution is largely a matter of centralized decisions, a planning model is more appropriate for the Drâa area. In this planning and simulation model for water use in the Drâa valley, the primary focus is on the interactions among water resources in detail, and the complementary use of groundwater and surface water respectively, which is an important aspect of management. For a holistic analysis of water management it is important to integrate water quantity as well as water quality aspects, as both affect crop productivity. With the help of scenario analysis, different policy options of water management can be evaluated.

Keywords: Irrigation systems, water management institutions, conjunctive water use, hydro-economic modeling, integrated river basin model

I-8.2.2.1 Introduction

In the following section, we analyze hydro-economic interactions in Morocco, with a special focus on the relationships between irrigation water and agricultural production in the Middle Drâa basin. After an overview on the importance of water for economic development in Morocco in general and in the Drâa valley in particular, the institutional structure of local water use management is discussed. Then,

we present the integrated hydro-economic modeling approach chosen for the Middle Drâa valley, which has been designed to analyze the linkages between agricultural production/income and environmental/hydrological constraints.

I-8.2.2.2 The importance of water use for economic development in Morocco

Economic perspectives gain in importance in an integrated water management approach, alongside the traditional hydrologic and engineering focuses. Especially in arid regions where water is a scarce and therefore very valuable production factor, the integration of economic aspects can help to support more efficient and more sustainable water use in the long run.

Water is a scarce resource in Morocco, especially in the southern parts, which have very low average annual rainfall (106 mm in Ouarzazate; 72 mm in Zagora). Agriculture remains a major sector in the Moroccan economy and contributes to 24% of the country's GDP (OECD 2008, n); however, agricultural production is largely dependent on irrigation water. Therefore, an analysis of the linkage between water availability and agricultural production and thus economic development is of utmost importance in this arid region.

Agricultural production and water resources are very heterogeneous in Morocco. Whereas some northern river basins are characterized by high annual rainfall and large scale irrigation perimeters with export production of fruits and vegetables, the majority of the southern river basins are arid regions with small scale irrigation perimeters and small farms with scattered fields. The latter case can be found in the Drâa river basin. Here, agriculture is the major activity for the rural population and contributes to household income besides its important function of food supply. Due to sparse rainfall, agricultural production is largely reliant on irrigation water. To ensure a more stable water supply for the oases, a reservoir was built in 1972 with the aims of preventing floods, assuring a water supply for irrigation and producing energy from hydropower (ORMVAO 1995). However, in times of water scarcity, the reservoir does not supply enough water for the irrigation of the entire agricultural area of the Middle Drâa valley. Also, water is not released continuously, but in periods that are often not sufficient for the crop water requirements. This volatile water availability has encouraged farmers to construct wells and supplement river water irrigation with more expensive, but more reliable, groundwater irrigation. This has resulted in the unsustainable depletion of the groundwater resources (see subsect. I-6.2.3) and has had negative effects on agricultural production and farm income.

I-8.2.2.3 Traditional water management in the Drâa oases

Due to its remote location south of the Atlas Mountains, the Drâa valley's water management was traditionally controlled by local elites on the village level and, to a minor extent, by regional elites, particularly religious orders and militarily superior nomadic tribes. Irrigation water was mostly diverted from the Drâa river, with the upstream communities enjoying the advantage of first come, first serve. The most important structure of local surface water irrigation systems is the so-called *segia* (pl. *suāgi*), a subsystem of irrigation canals originating from a tapping point at the river. Each *segia* was typically owned, managed, and defended by several villages. For instance, the *segia* Arnou in the Oasis of Tinzouline, which was investigated by Liebelt (2003), provides irrigation water to nine villages with 611 households. In the early eighties, 89 *suāgi* were counted in the Drâa valley (Ouhajou 1996).

Consisting of a system of a main canal and several branch connections, a *segia* is a technical system that constitutes an irrigation perimeter. However, it also represents a social entity of water users with a high degree of institutional organization, characterized by a separation of organizational and judicial functions. The property rights traditionally belong to an assembly (*ǧma'a*) of water users, owners of water rights, landowners, and village representatives. The water rights of individual users and the rules governing water distribution rarely existed in written form and had to be memorized by the owners.

The informal user assembly elects an *'āmil* (lit. laborer) who is often responsible for this task. Ideally, the *'āmil* is a member of the user association renowned for his honesty and impartiality, often combined with an economically peripheral position among the water owners and users (Hammoudi 1985). Moreover, many user assemblies appointed one or several 'experts'. While the *'āmil* was responsible for organizing the distribution of water and the maintenance of the canal infrastructure, the experts performed judicial functions such as arbitrating conflicts among members and sanctioning violations of rules.

Water use rights within a *segia* are bound to families, and imply the right to divert a certain share – not an absolute amount – of the water available to the *segia* to a field of the users' choice. The sequence of water diversion to a certain user is pre-determined within a village. The sequence of access to water among the villages constituting a *segia*, by contrast, is often determined by lot. Regarding the relation of water rights and land ownership, two systems can be found in the Drâa valley. In the dominating *melk* system, water rights are assigned independently of land ownership and may also be traded separately. In the less common *allām* system, water rights are tied to land ownership and can only be traded as a bundle. Water rights are bequeathed in a patrilinear fashion and are bound to a specific *segia*.

I-8.2.2.4 The push for modernization

With the increasing integration of the Drâa region into the Moroccan state in the 20th century, traditional institutions for water management have increasingly come into conflict with modernization efforts by the central government. Under the French protectorate, the colonial administration made irrigation policy one of its core areas of activity, aiming at the creation of one million hectares of irrigated land to produce exportable fruits and vegetables, and to ensure the provision of food to a swiftly growing population (Swearingen 1987). The erection of large dams was the most important technical tool used to increase the irrigated area, resulting in the completion of 14 large dams during the colonial era. However, running a dam for irrigation and freshwater supply will inevitably interfere with the already existing systems of river and groundwater use, a problem that was initially underestimated by planners. Essentially, establishing and running a dam represents a regional centralization of water management in both technical and institutional terms. Traditional water management schemes at the local level, such as the *segia* described above, will be faced with fundamental changes in expected water availability. Without a large dam, water availability depends on natural river flow and, to a minor extent, on the extraction by *suāgi* located upstream. A large dam, by contrast, allows national authorities to control the water supply at the local level throughout the year. As water users at the local level lose control over their access to water, their traditional water rights are most likely devalued.

After the Mansour Eddhabi Dam was put into operation to regulate the Drâa river in 1972, the ORMVAO (the ORMVA of Ouarzazate which is responsible for the Drâa valley) had to devise new water distribution rules among the six Drâa oases. While the share of water that was allocated to an oasis was based on that oasis' share in the total irrigated land of all oases supplied,[1] the downstream, southern oases were served first and the most upstream oases last. These new rules meant a substantial change in the 'traditional' water distribution. Before 1972, the downstream oases either had to take the water that the upstream users left over, or they managed to obtain more water through inter-oasis bargaining or the ruling of regional power elites.

Until today, water policy in Morocco is built on the goals incorporated in the code des investissements, from 1969. Investment should be concentrated on the large irrigation perimeters, which should be controlled by public authorities. For this purpose, the ORMVAs (*Offices regionales de mise en valeur agricole*) were established in the nine largest irrigation perimeters, among them the Drâa valley. While the ORMVAs were responsible for dam management and regional water distribution, the local branches of the ORMVAs, the CMVs (*Centres de Mise en Valeur*) deliver advisory services. Moreover, they initiate local water user groups

[1] This distributional rule is applied in the MIVAD simulation model to govern water allocation among the six Drâa oases. See the description of the MIVAD model below.

(AUEAs, *Associations d'usagers d'eau agricole*) that are supposed to replace the traditional water user associations. The boards of these AUEAs consist of six members elected by the assembly of the AUEA, plus a seventh board member who by legal requirement has to be a civil servant from the local CMV. Moreover, each user of agricultural surface water has to be organized in an AUEA. In this way the Moroccan state attempts to increase its influence on water uses, users, and owners of water rights on the local level.

The initial version of the *code des investissements* pursued the wholesale expropriation and compensation of owners of water rights as far as they were deemed incompatible with modern water infrastructure and institutions. This buyout of water rights, however, was never seriously implemented due to local resistance, particularly at the beginning of the eighties when the problems encountered as a result of the 'big dam' approach - high costs, environmental damage and local resistance, among other things - could no longer be ignored. Since then, the focus of national water policy has shifted towards smaller perimeters and attempts at reconciliation between modern and traditional institutions.

I-8.2.2.5 The resilience of traditional water institutions

The compulsory establishment of the AUEAs as water user groups in the eighties and nineties was the cornerstone of this policy, but the traditional water management institutions of the *segia* system proved to be much more resilient than the modernizers expected. A survey of the AUEA of Arnou in the Oasis of Tinzouline in 2003 by Liebelt (2003) shows that many of the institutional patterns of the *segia* system described above have survived even after the AUEA was founded, particularly the role of the *'āmil*. This water user group was perceived to be largely dysfunctional by its members at the time of the investigation, an impression that was supported by the obvious decay of both the traditional and modern parts of the canal system of the *segia*. However, the poor performance of the AUEA can only partly be attributed to inherent institutional incompatibilities; it is also due to the plain fact that a series of droughts in recent years had made water deliveries to the Drâa oases a rare event. The combined effect of drought, increased cultivation areas and the availability of motor pumps have induced farmers to switch from surface water to groundwater as the prime source for irrigation.

This development changes the perception of water by its users from a previously common good into a private good. But even though groundwater pumping appears to be a private matter to most farmers, the hydrological conditions in the Drâa valley reveal close relations between surface and groundwater. First, the available groundwater resources in the shallow aquifers below the Drâa oases are mainly recharged by infiltration of river water. Moreover, the same aquifers are exploited by numerous farmers, making groundwater also a common pool resource and its management a public issue on the local and regional levels. The hydro-economic

implications of this dual nature of water resources in the Drâa valley are discussed in the next section.

I-8.2.2.6 Agricultural production and available water resources

Agriculture is by far the largest user of water in the region. Farmers depend on water to irrigate their fields, as rain fed agriculture is not possible and is hardly practiced. According to Heidecke (personal comunication), agricultural water use takes up approximately 98% of the total water use of the oases in the Middle Drâa valley. Domestic water use and water use for tourism make up only a minor share of the total water use. This figure may change in the future due to a rising demand for drinking water and increasing tourist activities.

The major crops cultivated in the Drâa valley are cereals and date palms. Other important crops are vegetables and fodder in the form of alfalfa. Table I-8.2.2 depicts crop production in the six Drâa oases and outlines the differences of crop production between the oases. Maize and henna, for example, are rarely cultivated in the southern oases due to water scarcity during the summer months.

Table I-8.2.2: Crops cultivated in hectare and number of date palms in the six Drâa oases (Source: ORMVAO).

	Cereals	Maize	Vegetables	Legumes	Alfalfa	Henna	Total	No. of Date palms [in 1000]
Mezguita	2,600	200	95	75	850	120	3,740	271
Tinzouline	1,900	100	215	40	550	150	2,855	185
Ternata	4,700	-	692	36	1,190	180	6,798	331
Fezouata	-	-	77	5	510	40	2,832	254
Ktaoua	4,900	-	225	58	550	60	5,803	245
Mhamid	1,900	-	35	22	200	0	2,157	131
Total	18,200	-	1,349	236	3,850	550	24,185	1,417

Surface water used to be provided by the Drâa river, but since the construction of the reservoir upstream the Drâa river, water is only released in monthly periods in so-called *lâchers*. Originally, the reservoir and the *lâchers* were expected to stabilize the water supply for irrigation and drinking water demands, but due to sedimentation and evaporation, the capacity of the reservoir has decreased and less water is supplied to the farmers. Surface water distribution is practiced via a complex channel system and distributed according to traditional water rights among the farmers of a village within the oases.

Groundwater, in contrast, is locally available from the aquifers, but local resource endowments also differ among the oases, as depicted in table I-8.2.3. Fezouata has the largest reserves in natural groundwater resources, whereas Mhamid and Mezguita have the smallest groundwater resources (more detailed information of the groundwater dynamics can be found in subsection I-6.2.3).

Table I-8.2.3: Area and volumes of aquifers in the Drâa oases (Source: Heidecke et al. 2008, on the basis of Ouhajou 1996).

	Total area of the aquifers [km²]	Total natural reserves [Mm³]
Mezguita	45	22.5
Tinzouline	69	34.5
Ternata	178	71.3
Fezouata	196	127.1
Ktaoua	160	86.4
Mhamid	70	16.8

The southern oases in the Drâa valley are confronted with high salinity concentrations of the groundwater resources (see table I-8.2.4). Furthermore, the distribution of agricultural areas affected by salinity underlines the fact that the south is highly affected by water salinity and hence inferior soil quality. The affected area has increased over the last few years due to groundwater overexploitation and higher evaporation rates. A modeling approach that evaluates the linkages of agricultural production and water use needs to take these regional peculiarities into account. The MIVAD modeling approach developed in the IMPETUS project links water quantity and water quality to crop yield formation specifically for each of the six Drâa oases. This modeling approach will be described in detail in subsection I-8.2.2.7 below.

Table I-8.2.4: Salt concentration in groundwater [g/l], areas affected by salinisation [%] (Note: percentage values are rounded) (Source: Ouhajou 1996, ORMVAO 1996).

		Min [g/l]	Max [g/l]	Average [g/l]	1968 [%]	1980/81 [%]
North	Mezguita	0.3	3.5	1.5	12	24
	Tinzouline	0.4	7.0	2.5	31	32
	Ternata	0.4	8.0	2.5	35	42
	Fezouata	0.8	15.0	4.0	40	66
	Ktaoua	1.5	18.0	5.0	68	73
South	Mhamid	1.5	16.0	5.0	57	62

A simulation of the interlinkages of water use and farm income is important to be able to analyze and evaluate future development and possible policy options for more sustainable water use. In the following subsection, an overview of integrated hydro-economic modeling approaches and a detailed description of a model proposed for an integrated water management are given.

I-8.2.2.7 The hydro-economic simulation model MIVAD

To analyze water management at the river basin scale, an integrated analysis is necessary that evaluates water management from different perspectives and incorporates different disciplines in one modeling approach. A comprehensive overview of integrated hydro-economic river basin models has been provided by McKinney et al. (1999), and more recently by Brower and Hofkes (2008). Principally, integrated modeling approaches can be distinguished according to compartment models or holistic models. Compartment (or modular) modeling approaches loosely connect hydrologic and economic models by data exchange. The components can operate independently from each other, and a connection is created by data inputs from one part to the other in the form of exogenous variables. Holistic models solve all equations simultaneously and include different components, for example, economic, hydrologic, and agronomic components, at the same time. The holistic models are often constructed as node networks which represent the spatial relationships in a simplified way.

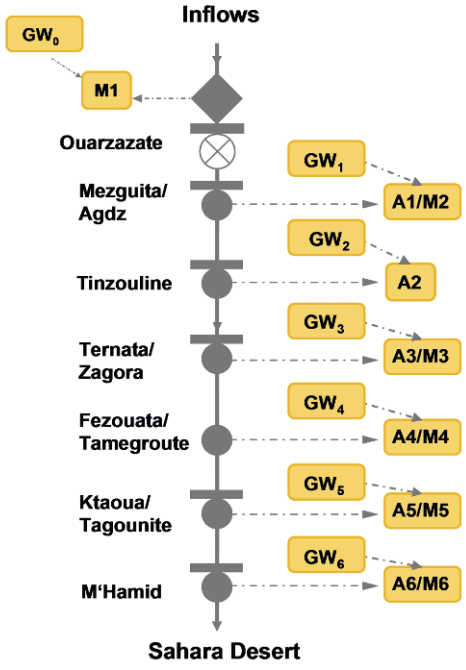

Fig. I-8.2.4: Node network of MIVAD.

During the last years the holistic models have been widely applied to many river basins and have been used for diverse scenario analysis. Ringler (2002) applied a holistic model for the Mekong basin to discuss optional water allocation strategies. Rosegrant et al. (2000) applied a holistic model for the Maipo basin. The MIVAD

model used for an integrated analysis of water management for the Drâa basin belongs to the category of holistic integrated hydro-economic models. MIVAD (*Modèle intégré dans la vallée du Drâa*) is constructed as a hydrologic-economic optimization model programmed in GAMS (General Algebraic Modeling System) with a node network representing demand and supply nodes for each of the six oases of the Middle Drâa valley: Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua, and Mhamid. The schematic framework of MIVAD is displayed in figure II-8.2.4. Spatial relationships are represented in the node network, representing different river flows, groundwater dynamics, small dams, reservoirs, and different water demand sites namely irrigation water demand and household water demand. The water distribution is modeled between the nodes.

Agricultural production is represented as a linear programming exercise involving six virtual farms for each of the oases (Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua, and Mhamid). The response of crop yields to water stress is represented with a modified Penman-Monteith function (FAO 1998). In MIVAD, this physiological production function is extended to include effects of salinity in irrigation water on crop yields, as described in detail by Heidecke and Kuhn (2007).

With this extension, the crop yields of eight crops cultivated in the oases are calculated by reducing the maximum yield of a crop in the region under optimal conditions by a water deficit factor and a salinity reduction factor. It is assumed that the maximum crop yield is achieved under perfect climatic conditions. The actual yield is lower than the maximum yield due to insufficient water supply to

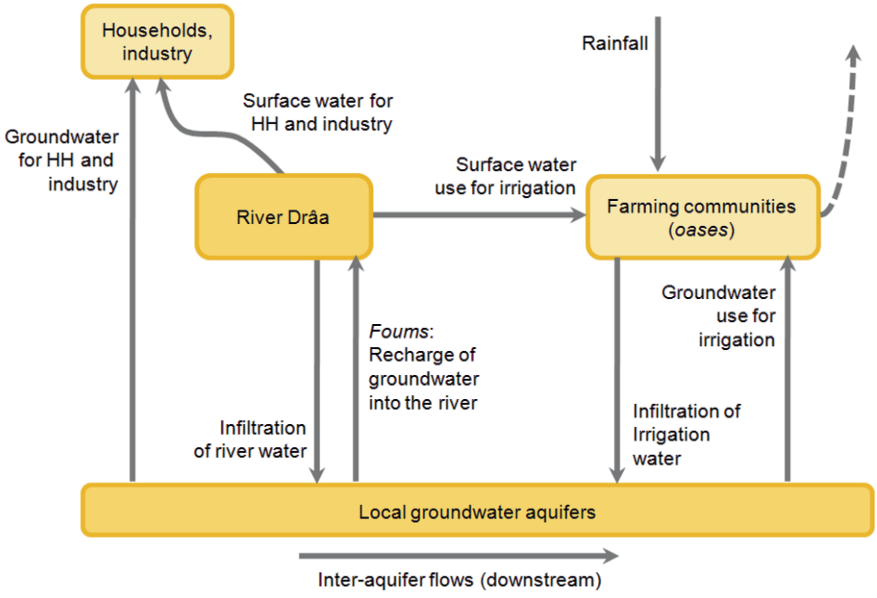

Fig. I-8.2.5: Hydrological interactions in MIVAD.

the crop and salinity response. The yield reduction factor due to salinity is calculated on the basis of a modified discount function derived from work by Steppuhn et al. (2005).

Moreover, MIVAD incorporates a variety of constraints, bounds, and balance equations related to hydrology (river, groundwater and reservoir balance), agronomy (crop yield response, area and cropping patterns) and general technological aspects (hydropower, pumping by public and private agents) all of which have to be controlled. A detailed model description can be found in Heidecke and Kuhn (2006) and Heidecke et al. (2008).

Within the scope of the problem clusters and interdisciplinary work, the hydrogeological component is consistent with the model BIL (Klose et al. 2008) described in subsection I-6.2.3. The hydrological modeling network of the Drâa river basin actually starts with the river node that defines the exogenous monthly inflows into the Mansour Eddahbi reservoir from the High Atlas Mountains. From the reservoir, water is released to the Drâa river and flows downstream, partly infiltrating and percolating to the alluvial aquifers subjacent to each oasis (see fig. I-8.2.5).

In the Drâa valley, aquifers are not closed entities, but are interconnected by discharges in the same direction as the river flow. Lateral inflows from rain water infiltrating the catchment area of each aquifer also contribute to groundwater recharge, but have played only a minor role in most years. Water that infiltrates from the river bed into the aquifers is an important contribution to the groundwater balance. Sometimes reservoir releases are used solely to replenish the groundwater bodies in the river basin. The groundwater balance is thus implemented as follows:

Groundwater discharge to the next river node
=
+ Groundwater lateral afflux
+ Discharge from the previous aquifer
+ Losses from the use of irrigation water
+ Groundwater pumping losses (for municipal uses)
+ Losses from the use of river water
+ Groundwater recharge from rain
- Groundwater pumping for municipal uses
- Groundwater pumping for agricultural uses
- Groundwater discharge to the next aquifer
- Groundwater discharge to the next river node

A detailed description of the hydro-geological interactions and the implications for economic aspects of water use can be found in Heidecke et al. (2008). Domestic water use is assumed to be exogenous in this version of the model, but is varying over the years depending on population growth.

The model is to maximize agricultural revenues over all oases and is solved simultaneously in monthly steps. Table I-8.2.5 displays selected results for a dry, a normal and a wet year, which are distinguished between their annual inflows

into the reservoir. One year is modeled as a static comparative simulation exercise. The average year represents average inflows into the reservoir from 1971 to 2002 which are 340 Mm^3. The wet year represents the upper quartile of these inflows and the dry year represents the lower quartile, with 446 and 105 Mm^3, respectively. The results show that groundwater is hardly used in wet to average years, as surface water is sufficient to irrigate total agricultural area (100% of cropland is cultivated) and because groundwater is more costly than surface water and is of lower quality. However, in times of scarcity, the amount of groundwater used for irrigation increases immensely because, although it imposes extraction costs, groundwater use is profitable. In the scarcity scenario, however, the total water availability is only sufficient to cultivate 65% of total available crop land. Thus, agricultural income declines.

Table I-8.2.5: Selected results of the MIVAD model for a dry, a normal and a wet year (Note: wet year is referring to reservoir inflows of 446 Mm^3, the average year: 340 Mm^3 and the dry year 105 Mm^3).

	Wet year	Average year	Dry Year
Ag river water use	422.00	328.00	131.00
Ag GW use	0.13	1.85	101.00
Shadow price	0.72	1.54	2.52
Use of crop area [%]	100.00	100.00	65.00
Agricultural income [M DH]	555.00	475.00	198.00

For the scenario analysis in Part II of this book, the model is run over several years as a recursive-dynamic model, with each year divided into twelve months that are solved consecutively.

I-8.2.2.8 Conclusions

An integrated analysis of the river basin level in the Drâa valley is necessary to understand the interaction processes between water and agriculture. Any analysis should account for the institutional arrangements governing access of farm households to irrigation water, as well as its distribution among villages and oases. Moreover, hydrological aspects need to be combined with agricultural production characteristics (cultivation patterns and technologies used), as farmers are still by far the most important water consumers in the region. Nevertheless, domestic water use should be represented within an integrated analysis as it is of the highest priority and is likely to increase in the future. In contrast to the market model used in Benin (BenIMPACT), a planning model is more appropriate for the Drâa area, as water markets have not yet emerged and water distribution is largely a matter

of centralized decisions. The model thus differs from the model used in Benin because in the Drâa valley the focus is directed at the interactions of water resources in detail, and the coordinated use of groundwater and surface water, which is an important management aspect. For a holistic analysis of water management it is important to integrate water quantity as well as water quality aspects, as both affect crop productivity. Differences between the oases should also be taken into account as cultivation patterns differ between the oases.

The MIVAD modeling tool provides a comprehensive picture of water management. With the help of scenario analysis, different policy options of water management can be evaluated. These are further analyzed in Part II of this book.

References (I-8.2.2)

Brower R, Hofkes M (2008) Integrated hydro-economic modelling: Approaches, key issues and future research directions. Ecol Econ 66:16-22

FAO (Food and Agriculture Organization) (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and drainage paper No. 56. FAO, Rome

Hammoudi A (1985) Substance and Relation: Water Rights and Water Distribution in the Dra Valley. In: Mayer AE (ed) Property, Social Structure and Law in the Modern Middle East, pp. 27-57. State University of New York Press, New York

Heidecke C, Kuhn A (2006) The integrated model of the Drâa valley MIVAD (Modèle Intégré de la Vallée du Drâa) - Technical Documentation. University of Bonn. http://www.ilr1.uni-bonn.de/agpo/rsrch/impetus/doc/mivad-docu.pdf. Accessed 23 October 2009

Heidecke C, Kuhn A (2007) Considering salinity effects on crop yields in hydro-economic modelling - the case of a semi arid river basin in Morocco. Water Resour Manag IV. WIT Press, Southampton

Heidecke C, Kuhn A, Klose S (2008) Water pricing options for the Middle Drâa River Basin in Morocco. AfJARE 2(2):170-187

Klose S, Reichert B, Lahmouri A (2008) Management options for a sustainable groundwater use in the Middle Drâa Oases under the pressure of climatic changes. In: Zereini F, Hötzl H (eds) Climatic Changes and Water Resources in the Middle East and in North Africa, pp. 179-196. Springer, Heidelberg

Liebelt C (2003) Die Wasserwirtschaft im südmarokkanischen Dratal im Spannungsfeld von lokaler und staatlicher Ressourcenkontrolle. Research Report for IMPETUS Sub-Project B-4-1, Institut für Völkerkunde, Cologne University. http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/ publikationsliste/826_abschlussbericht_B-4-1.pdf. Accessed 23 October 2009

McKinney D, Cai X, Rosegrant MW, Ringler C, Scott CA (1999) Modeling water resources management at the basin level: Review and future directions. SWIM Paper No. 6. International Water Management Institute, Colombo

ORMVAO (1995) Etude d'amélioration de l'exploitation des systèmes d'irrigation et de drainage de l'ORMVAO- Phase 1: Diagnostic de la situation actuelle. Rapport détaille du diagnostic Vol 1. Ouarzazate

Ouhajou L (1996) Espace Hydraulique et Société au Maroc- Cas des Système d'irrigation dans la vallée du Drâa. Faculté des Lettres et des Sciences Humaines. Thèse et Mémoire. Agadir

Ringler C (2002) Optimal allocation and use of water resources in the Mekong river basin: A multi-country and intersectoral analysis. Peter Lang, Frankfurt

Rosegrant MW, Ringler C, McKinney DC, Cai X, Keller A, Donoso G (2000) Integrated economic-hydrologic water modelling at the basin scale: the Maipo River Basin. Agr Econ 24(1):33-46

Steppuhn H, van Genuchten MT, Grieve CM (2005) Root-zone salinity II: Indices for Tolerance in Agricultural Cops. Crop Sci 45:221-232

Swearingen WD (1987) Moroccan Mirages. Agrarian Dreams and Deceptions, 1912-1986. Princeton University Press, Princeton





9 Summary

I-9 Summary

P. Speth and A. H. Fink

The overall goal of IMPETUS aimed at developing an interdisciplinary, integrative approach to mitigating region-specific risks of Global Change as they relate to the hydrological cycle for two differing catchments. The target areas were the Ouémé basin in Benin and the Drâa catchment in Morocco. Ultimately, decision makers in Benin and Morocco were given tools that have helped them analyze decision-making problems and understand the phenomena underlying these problems. This then allowed these parties to assess the impact of their decisions and to implement sustainable management options for water resources that are so vital to life. Results of these different options can be compared and evaluated for different scenarios using *Spatial Decision Support Systems (SDSSs), Information Systems (ISs)*, and *Monitoring Tools (MTs)*. These tools are described in Part II of this book. Target years were chosen as 2025 for Benin and 2020 for Morocco based on pre-existing, long-term government strategy papers.

To develop efficient and user-friendly management tools, it is necessary to have a sufficient *database* available, to achieve an exhaustive understanding of relevant *processes* steering the hydrological cycle, and to have calibrated and validated computer *models* that are able to simulate underlying processes at one's disposal. The achievements in these three areas are presented in Part I, are summarized below, and they provide the scientific basis for Part II of this book.

Characteristics of the catchments

The Ouémé catchment

The Ouémé catchment covers an area of approximately 50,000 km^2. The Ouémé river drains to the south into Lake Nokoué and flows through the coastal lagoon system into the Gulf of Guinea. Wetlands are found in the south of Benin. Inland valleys (in French: *bas fonds*) that are regularly flooded during the rainy season are widespread and have the potential to augment food production. In the north, the Upper Ouémé Valley (in French: *Haute Vallée de l'Ouémé* - HVO) in Central Benin, with an area of approximately 14,000 km^2, has been chosen as a region of focused investigations. A "super test site" concept was applied in the HVO. Specifically, the Aguima catchment (approximately 30 km^2) was intensively studied to identify key hydrological processes. The landscape is a weakly undulated pediplain with isolated inselbergs. The highest point in the HVO (Inselberg Soubakperou) has an elevation of 620 m. The natural vegetation is a mosaic of woody savannas and small forest islands. Some azonal vegetation units are found in certain locations (e.g., inland valleys, gallery forests, or inselbergs). Vegetation gradients in the Ouémé catchment

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are smooth, and the ecological units are not nearly as diverse as those found in the second IMPETUS study region, the Drâa catchment in Morocco. Population growth has had a major impact on land use and land cover change in Benin. Population growth is greater than 3% per year and is distributed very unevenly, showing a strong negative correlation with the existing population density. While the growth rate in the densely populated southern portion of Benin is approximately 2% per year, the less densely populated regions in Central Benin show annual growth rates of up to 6% per year. The high growth rates in these regions are due to migrations from northern and southern Benin caused by land scarcity.

The Drâa catchment

The Drâa catchment in Morocco spreads from the principle mountain divide of the Central High Atlas Mountains southward to the pre-Saharan foothills. It encompasses complex climatological, hydrological, and vegetation regimes due to its high elevation range between Lake Iriki (421 m) and M'Goun (4,071 m). A distinct gradient of rainfall, temperature, and therefore hydrological processes and vegetation is observed in the Upper and Middle Drâa from south to north that follows an increase in altitude. Most of the IMPETUS project was focused on the Upper and Middle Drâa catchments. The Upper Drâa extends over an area of approximately 15,000 km^2, and its tributaries drain into the Mansour Eddahbi reservoir. Among its tributaries, only the Dades river flows permanently because of its origins in the High Atlas Mountains, which are characterized by higher precipitation amounts and karstic aquifers. Some winter precipitation falls as snow that serves as a natural water reservoir. In the spring, melting snow cover feeds the rivers and reservoirs of the Upper Drâa basin. Before the Mansour Eddahbi reservoir near Ouarzazate was built in 1972, runoff frequently reached Lake Iriki during floods. This is an endorheic lake of the Drâa basin, as the amount of water is not sufficient to flow the last 750 km to the Atlantic Ocean (Lower Drâa valley). The reservoir was constructed to ensure irrigation, generate hydroelectric energy, and reduce flood risks. The region in which a significant amount of discharge is generated is above an altitude of 1,900 m, and this high elevation area accounts for one third of the area in which half of the precipitation falls. All of the remaining rivers in this region only flow periodically or episodically. The contribution of these remaining rivers to total discharge is low and difficult to quantify due to missing gauging stations. Water stored in the reservoir is the water supply of Ouarzazate and other cities. Water losses due to evaporation are significantly higher than urban water requirements. Outlets from the Mansour Eddahbi reservoir represent the major water input of the Middle Drâa valley (approximately 15,000 km^2). However, outlets depend on the filling level and show strong interannual variability. The Middle Drâa valley includes six river oases downstream of the Mansour Eddahbi reservoir.

The vegetation of the Drâa basin is a transition zone between Mediterranean shrublands and Saharan desert biomes. From the High Atlas Mountains southward, the vegetation follows a joint altitudinal and aridity gradient that results in

a sharp transition from sub-humid to arid ecosystems. Human land use has degraded natural vegetation patterns to varying degrees. Agriculture is only possible with irrigation that uses either channeled river water or pumped groundwater. Irrigated agriculture covers approximately 2% of the Upper and Middle Drâa area (total oasis area).

Intensified emigration from marginalized, rural communes into urban centers is currently the most important demographic phenomenon in the provinces of Quarzazate and Zagora. People migrate not only nationally and internationally but also intra-regionally in search of income opportunities other than subsistence farming. Because urban centers are growing much faster (3.1% average annual growth) than rural areas (0.8% average annual growth), urbanized areas play a crucial role in the region's demographic development.

Database

As summarized in the preceding paragraphs, the climatic, ecological, and hydrological environments of the Ouémé and Drâa catchments are very different. Little hydro-meteorological and vegetation data are available for either region. This data scarcity is typical for many African catchments with respect to both the spatial density of measurement stations and long-term homogeneous time series. These data are necessary for process studies and trend analyses as well as for model initialization and validation. Measurement concepts developed under IMPETUS considered these challenges and provided a database for knowledge-based adaptations to the changing environment. In Benin, the existing national hydro-meteorological monitoring networks were improved in some regions, with a focus on the Upper Ouémé catchment. Here, a "super test site" was established. In the Drâa catchment, thirteen weather stations were deployed along climate, hygric, and vegetation gradients that range from the Saharan foothills of the Antiatlas Mountains to the summits of the High Atlas Mountains. Snow depth and water equivalents of the snow pack were monitored at these higher elevations. Vegetation test sites were attached to meteorological enclosures, including fenced exclosures, to monitor climate-dependent vegetation development with and without grazing. The variability of geological settings and land use was also considered before sites were chosen. This network was complemented by water level recorders, primarily in higher parts of the High Atlas Mountains. The IMPETUS station transect in Morocco is unique because it covers the entire ecological gradient typically found on the Saharan side of the Atlas Mountains. Additionally, surveys were carried out, especially in the fields of socio-economics, anthropology, and medicine.

Data have been stored in databases and are available to everyone interested via the internet. Data are also available online as printed and digital atlases of Benin and Morocco. The internet addresses for these data are provided in section II-1.

Process understanding and modeling approaches

The Ouémé catchment in Benin has a sub-humid climate of the outer tropics that is controlled largely by the West African monsoon circulation. The bulk of annual precipitation occurs during the rainy season of the boreal summer. The rainy season is bimodal in the south and unimodal in the north. The dry season is characterized by dry, dusty, northeasterly Harmattan winds. The dynamics of rainfall-bearing weather systems are impacted by large-scale forcing mechanisms such as the North Atlantic Oscillation (NAO), the El Niño-Southern Oscillation (ENSO), sea surface temperatures (SSTs) of tropical oceans, atmospheric aerosols, and land surface conditions. These teleconnections are non-stationary, i.e., they vary over time scales of decades. From a regional Beninese perspective, meteorological research under IMPETUS has elucidated different types of rainfall that occur under seasonally-varying meteorological conditions. Furthermore, this research has shown that changes in vegetative cover and man-made land cover must be considered when evaluating Climate Change.

Rainfall variability in northern Morocco and the Atlas Mountains is influenced by maritime Atlantic and Mediterranean weather systems, which are statistically significantly connected to the NAO and ENSO. In northern parts of the Drâa catchment, this variability leads to a humid/sub-humid climate with a unimodal distribution of annual rainfall. Maximum precipitation occurs in the winter and spring in the northern Drâa catchment, whereas there is no definite maximum in the arid southern parts of the catchment. One notable and novel discovery of the IMPETUS project has elucidated processes pertinent to rainfall variability south of the main divide of the Atlas Mountains. Here, tropical-extratropical interactions (TEIs) play a dominant role in extreme rainfall events that are fed by tropical moisture sources. The frequency of these events peaks in the fall and spring, but these events also occur in the winter and summer. During the summer, precipitation is often related to thunderstorms and showers triggered over the Atlas Mountains. Evaporation associated with this convection generates extended pools of cool air that transport moisture into the northwestern Sahara.

Complex mechanisms responsible for rainfall variations at various spatial and temporal scales confirm the need to apply complex atmospheric modeling and regionalization approaches over a range of climatic scales to obtain meaningful climate projections. These approaches were followed under IMPETUS for both the Drâa and Ouémé catchments. A hierarchy of climate models and different downscaling methods capable of reproducing the major characteristics of rainfall-producing weather systems was applied to project future plausible pathways of Climate Change in both catchments. This is detailed in part II of this book.

Sustainable water resource management requires a thorough knowledge of water availability and demand at different spatial and temporal scales. In addition, in the fields of hydrology and hydrogeology, it is necessary to obtain a process understanding and to quantify anthropogenic effects (e.g., construction of reservoirs) and environmental changes (e.g., Climate Change, land use change). Thus, field

experiments were conducted using, for example, measurements of infiltration and hydraulic conductivity. With regard to scale considerations and sampling, a problem exists whereby sampling often takes place on very small spatial and temporal scales that are sometimes smaller than process scales. While process scales depend on the problem to be solved or the question to be answered, information scales dictate the scale on which information is required (e.g., for decision-making). Model scales are situated between these different scales. Temporal and spatial discretization must consider sampling, process, and information scales. The experimental approaches for the two catchments were chosen considering these scale requirements.

For the Ouémé catchment, a concept was developed that starts at the small catchment scale (a few km^2) for studying hydrological processes because data were limited on climate and land use in West Africa. For this purpose, a physically-based model was developed and applied successfully at the local scale. Findings were transferred to larger catchment scales (approximately 50,000 km^2). For regional scales, a conceptual semi-distributed model was applied. For the upscaling process, a physical local scale model was used as a benchmark, and the conceptual model was successfully calibrated and validated at several gauging stations at different spatial and temporal scales. The validation of the conceptual model revealed that the model is applicable to the region, that it is able to reproduce differences in hydrological behavior due to differences in land use and climate conditions, and that it is accurate in both wet and dry periods. Therefore, the developed hierarchical approach is a good strategy for Global Change scenario analyses as described in Part II of this book. With regard to soil erosion, a regional approach was used to identify erosion hotspots. Current hotspots of soil erosion were identified and their existence was verified in the field. These hotspots were further analyzed using a special model system that was also able to adequately reproduce recent water and sediment dynamics. This model system can also be used for scenario analysis.

In contrast to the hierarchical approach applied to the Ouémé catchment, the hydrological analysis of the Drâa catchment used a local scale approach. Specifically, while this approach followed temperature and rainfall gradients on a local scale, a regional approach was used to quantify runoff in the Upper Drâa valley. In between these two approaches lies a linear oasis structure approach, in which water consumption as well as soil salinity was studied. These analyses showed that the developed hydrological, groundwater, salinity, and soil erosion models effectively represented relevant processes. Thus, these models can successfully process scenario calculations introduced in Part II of this book.

The state of the anthroposphere is provided for the Beninese and Moroccan research regions with special emphasis on the human use of water and land resources. The impact of selected demographic, anthropological, and economic characteristics and processes on resource use is given special attention. For instance, gender is an important factor affecting household water use in rural Benin; another example is friction between different institutional layers that govern the

irrigation schemes in the Drâa valley. In both regions, knowledge gained about governing processes of the anthroposphere provided input into numerical simulation models with both biophysical and economic features. The features of these models have also been briefly described, and they form the basis for Part II of this book.

Part II

Future projections and decision support

II





1 Introduction: The IMPETUS method

II-1 Introduction: The IMPETUS method

P. Speth and B. Diekkrüger

Regional climate models that take land use and land cover changes into account indicate a general decrease in rainfall and prominent surface heating in sub-Saharan Africa until 2050 (see sect. II-3.2). The high population growth predicted in this period is expected to cause rapid land use changes and to strongly influence water availability and demand. In this context, the IMPETUS research project was not intended to offer a prescription of rigid options for sustainable management of the hydrological cycle. Rather, it was intended to support the decision-making process within project countries. For this purpose, tools have been developed that allow for the comparison and balancing of different options with the aid of *Spatial Decision Support Systems (SDSSs)*, *Information Systems (ISs)*, and *Monitoring Tools (MTs)*. The intention is to help decision makers by providing them with efficient and user-friendly tools for analyzing and managing decision-making problems and underlying phenomena. Target areas for this research were the Ouémé basin in Benin and the Drâa catchment in Morocco. Target years were chosen as 2025 for Benin and 2020 for Morocco based on pre-existing, long-term government strategy papers.

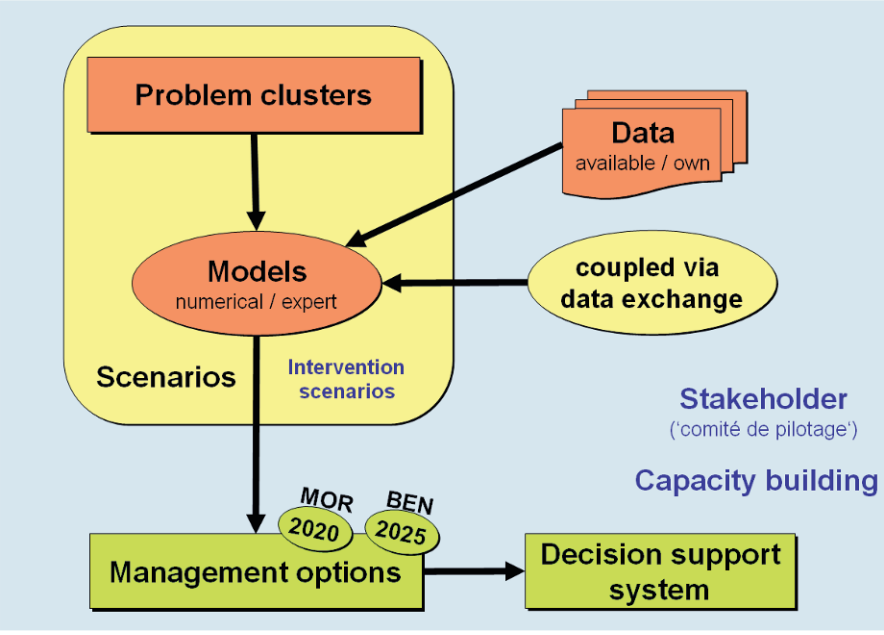

Fig. II-1.1: Schematic representation of the IMPETUS approach. The work is organized into problem clusters. Adapted models are applied to compute scenarios of further development.

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Decision-making requires an exhaustive knowledge of processes, driving forces, stakeholders, and possibilities. Furthermore, decision-making requires adapted modeling systems that are able to adequately answer "what if" questions. To provide suggestions for decision-making support, the methodology summarized in Fig. II-1.1 was applied as the IMPETUS approach. The IMPETUS project started in the year 2000 and was structured in three phases, each of which lasted for three years.

In the first three-year project phase, the focus was mainly on the diagnosis of different aspects of the water budget and their interactions as documented in Part I of this book. Processes and state variables are often analyzed in an interdisciplinary way. Because decision-making for water management is a complex task and requires the cooperation of numerous disciplines, interdisciplinary research is the key to sustainable development. Decisions also require new and adapted technologies. Decision-making for water management is always undertaken by balancing ecological, economic, and social considerations. Therefore, no single solution exists for complex questions because the optimal solution depends on the weight assigned to different positions and the goals of the decision-making process. To adequately handle complexity, numerous *problem clusters* were defined. These are meta-problems that require multi-disciplinary analyses to draw conclusions for possible future developments. For nearly every problem cluster, SDSSs, ISs, or MTs were developed to provide tailored tools for decision-making. During the first project phase, pre-existing databases were of poor quality or incomplete for some of the disciplines involved. In these cases, intensive data acquisition campaigns and surveys were carried out, especially in the fields of socio-economics, anthropology, and medicine. For the better adaptation and validation of the natural science numerical models, existing national monitoring networks were enhanced in Morocco by installing measurement instrumentation along the gradient in elevation and aridity (see sect. I-4.3) and by setting up a "super test site" in Benin (see sect. I-4.1). *Data* were stored in databases and made available to any interested parties (cf. http://geonetwork.impetus.uni-koeln.de), including publication as the Digital Atlases of Benin[1] and Morocco[2]. Basic research was only conducted if the existing competence and experience levels proved to be insufficient.

IMPETUS has developed, calibrated, and validated computer *models* that describe underlying processes. A number of computer models were improved and adapted for the investigated regions. They covered all areas of interest, such as climatology, hydrology, agriculture, socio-economics, and health. These models

[1] Judex M, Thamm H-P (eds.) (2008), IMPETUS Atlas Benin. Research Results 2000–2007, Department of Geography, University of Bonn, Germany, ISBN-13 978-3-9810311-5-7 (French version: ISBN-13 978-3-9810311-8-8).
http://www.impetus.uni-koeln.de/en/publications/digital-print-atlas.html. Accessed 12 November 2009.

[2] Schulz O, Judex M (eds.) (2008), IMPETUS Atlas Morocco. Research Results 2000–2007, Department of Geography, University of Bonn, Germany, ISBN-13 978-3-9810311-6-4 (French version: ISBN 978-3-9810311-7-1).
http://www.impetus.uni-koeln.de/en/publications/digital-print-atlas.html. Accessed 12 November 2009.

could be either *numerical* or *expert* models. Since integrating coupled models under a single system to construct a so-called Earth system model was deemed too complex, disciplinary models were coupled via *data exchange* ("loosely coupled models"). Future changes cannot be predicted precisely because of uncertainties in socio-economic scenarios and because of substantial model uncertainty. Therefore, the common approach is to assess the bandwidth range of possible future developments with the help of likely *scenarios*. It is important to stress that scenarios cannot be quantified by probability. The scenarios, including *intervention scenarios*, were developed in close cooperation with project partners from Benin and Morocco. The coupling of models and the development of scenarios were the main tasks of the second three-year project phase of IMPETUS.

During the final three-year project phase, collected insights from all disciplines involved were used to develop and provide operational tools for local decision makers. Such *decision support systems* allow stakeholders to assess risks and likely impacts on regional and local scales.

Local *stakeholders* participated throughout different phases of the project. Furthermore, intensive *capacity building* of local partners was accomplished. Stakeholders at different levels (e.g. academic and institutional levels) were involved in the development and use of SDSSs, ISs, and MTs.

Problem clusters and models

Concrete integrative research under IMPETUS was organized into problem clusters, where the term "problem cluster" describes a set of comprehensive and complex problems that require a multi-disciplinary approach to be successfully analyzed and understood. Thus, future perspectives have to be considered when developing and implementing related solutions (see fig. II-1.1). Problem clusters covered a wide spectrum of socio-economic and environmental problems and their interactions. Scenarios were fed into the problem cluster via boundary conditions.

The analysis of future development was based mainly on suitable models. IMPETUS largely abstained from developing new models and instead used existing models after confirming their suitability. Models were adapted for the specific regional situation and sometimes for the local level. A comprehensive collection of models was gathered that could be utilized for different kinds of analyses required for each problem cluster. This model collection allowed for flexibility when approaching specific research questions. The concept utilized in IMPETUS was a loose coupling of different system components (disciplinary models) that depended on the questions being considered. Numerical models or expert models form the backbone of each problem cluster. Results from other models or problem clusters were used as inputs.

Problem clusters were grouped into the following subject areas:

- Food/livelihood security: A number of problem clusters deal with food production because it depends on a variety of factors, including soil quality, rainfall, and soil erosion.
- Hydrology: These problem clusters are related to water availability, water demand, and soil erosion.
- Land use: The development of land use, land cover, and related topics were analyzed.
- Society and health: This area includes not only population projection research but also water management, livelihood security, and microbial and viral pathogens such as malaria and adenoviruses.

Scenarios (for details see chap. II-3)

Scenarios of regional development were employed to determine the relevant driving forces. From these driving forces, the necessary boundary conditions for the models were derived to simulate the effects of global and regional change on water resources and related issues. Scenarios are consistent and plausible images of alternative futures that are comprehensive enough to support the decision-making process. A meaningful scenario integrates different societal, technological, environmental, economic, and demographic aspects of the system under investigation. Scenarios are not predictions and should not be quantified by probabilities. Instead, scenarios allow for the analysis and assessment of alternative development paths for complex systems through identification of the following: (1) the most important driving forces at national and regional levels; (2) sub-regional developments or events that are of national relevance; (3) the most important cross-links between national and regional development; and (4) the most important knowledge gaps and unanswered questions that warrant further action. Participation by societal actors plays an important role in the development of scenarios by helping to create scenarios that are up to date. Conversely, this participation prevents mistakes caused by incorrect or insufficient information and incorrect data interpretations, which can jeopardize the entire analysis.

A two-step approach was used to develop the scenarios used in IMPETUS. In the first step, a thorough analysis was performed using detailed field studies and surveys, which were a prerequisite due to sparse data in both catchments. Major driving forces and response indicators were identified that resulted in a characteristic, qualitative description that was summarized in a "qualitative trend-matrix". From this basic description, so-called "storylines" were developed that contained both qualitative and quantitative information on final driving forces. Quantification was performed with the help of different models. By definition, a storyline is a narrative description of a scenario that highlights the important characteristics and dynamics of the scenario and the relationships between key driving forces.

Climate is not a thematic issue explicitly described in the above-mentioned storylines of societal, economic, and ecological scenarios. Instead, three climate reference scenarios for each catchment were defined to serve as external drivers of more general scenarios. This procedure allowed for a more flexible combination of the two scenario types.

Decision support systems (for details see chap. II-2)

Decisions are complex and require adapted technology. IMPETUS has developed numerous SDSSs, ISs, and MTs to provide tailored tools for decision-making. This approach was possible because a framework has been developed that integrates different tools in a user-friendly way. A number of computer models were improved, adapted, and calibrated for application in the studied regions using the IMPETUS database. As mentioned above, these models address pertinent subjects such as climatology, hydrology, agriculture, socio-economics, and health. SDSSs are dynamic because they permit new information to be generated by running embedded models. In contrast, the information content of ISs is static but can be updated if necessary. MTs complement decision-support tools by providing near real-time data on the state of the continental hydrosphere or biosphere based on remote sensing techniques.

Stakeholder dialogue and capacity building

Throughout different stages of the IMPETUS project, the participation of local *stakeholders* was sought, and intensive *capacity building* of local partners was a major goal. This dialogue covered the development and use of scenarios as well as the application of SDSSs, ISs, and MTs, especially because these are main products of the project concerning the applicability in the countries. IMPETUS tools and systems can be used by many stakeholders, including: (i) decision makers interested in scenario analyses to assess possible decisions; (ii) scientists interested in improving approaches, models, and decision-making processes; and (iii) any party interested in the comprehensive database for further analysis and decision-making using approaches not yet considered.

Stakeholder dialogue and capacity development measures involved national administrations, academic institutions, communes, and individual users. This broad spectrum of collaboration fostered the sustainable implementation of IMPETUS tools in the studied countries. This is complemented by mirroring the extensive IMPETUS *database*[3] at various regional institutions and by making it also utilizable online to interested parties as web-based, digital atlases of Benin and Morocco.

[3] http://geonetwork.impetus.uni-koeln.de





2 The IMPETUS Spatial Decision Support Systems

2.1 Introduction

2.2 Spatial Decision Support Systems

2.3 The Scientific Model Integration pipeLine Engine Framework

2.4 Examples for Spatial Decison Support Systems, information systems and monitoring tools

- 2.4.1 Spatial Decision Support System PEDRO
- 2.4.2 IWEGS
- 2.4.3 Monitoring tool PRO-RES
- 2.4.4 LISUOC

2.5 Conclusions

II-2 The IMPETUS Spatial Decision Support Systems

A. Enders, B. Diekkrüger, R. Laudien, T. Gaiser, and G. Bareth

Abstract

Decision support is not only a question of mere technical assistance, but also of multiple facets. Besides scientific and organizational aspects, special attention must be paid to the societal aspects of decision support, because a decision can only be supported and taken when the social frame is considered. The different aspects of decision support and software development are presented here. Within the IMPETUS research project, the SMILE (Scientific Model Integration pipeLine Engine) framework has been developed, which integrates dynamic simulation models, information systems and monitoring tools for decision support. The developed framework is based on modern software technologies and tries to balance numerous contradicting aspects like the implementation of complex solutions with convenience of use.

As examples, two Spatial Decision Support Systems, one information system and one monitoring tool are presented and discussed. The flexibility of the SMILE framework in handling different aspects of decision support is shown.

Keywords: Decision support, information system, monitoring tool, SMILE framework, PEDRO, IWEGS, LISUOC, PRO-RES

II-2.1 Introduction

Research projects like IMPETUS are confronted with a number of requirements. From a purely scientific point of view, the focus is on data gathering, model development, model application and scenario development. However, these data and scientific results must be treated in a way that can further be used by the stakeholders in the investigated countries. The first challenge is not only to transfer data and results, but also to develop decision support tools for evaluating management options regarding water related problems. The second challenge is to enable stakeholders to use this highly complex information in the decision-making process. There are different possibilities to address the second challenge. All of them re-

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quire intensive communication, long-term planning and deep knowledge of the individual situations of the users and/or stakeholders. IMPETUS chose four of the various possibilities:

1. intense capacity development of local partners,
2. direct information transfer via a printed and a digital version of an Atlas, in which, main results of the research project are condensed,
3. direct data transfer via the IMPETUS Geonetwork Server including modeling results in addition to raw and processed data,
4. development of the IMPETUS Spatial Decision Support Systems, Information Systems and Monitoring Tools, including training of the stakeholders.

These different possibilities overlap to a significant degree. By combining them, synergy effects reduce the required effort and increase the benefits. Capacity Development was combined with the development of decision support tools and data transfer.

II-2.2 Spatial Decision Support Systems

Definitions of Decision Support Systems (DSSs) or Spatial Decision Support Systems (SDSSs) are manifold. In this study we use the following definitions: Decision Support Systems (DSSs) are interactive and flexible computer-based systems (Densham 1991). They are used for the identification and solution of complex, poorly structured problems to improve decision-making processes (Turban et al. 2004). Following Matthies et al. (2007), they should focus on the specific needs of the end-users and should be developed in an interactive process.

An SDSS (Manoli et al. 2001) differs from a DSS because of its spatial component, which plays a decisive role in the decision support process. Crossland et al. (1995) showed that the use of spatial data reduces decision time and increases the accuracy of the resultant decisions. However, the definitions of SDSSs disagree in whether numerical models are necessary. By refining the approach presented by Hahn (2001) and Vacik and Lexer (2001), figure II-2.2.1 illustrates the definition we use for the IMPETUS SDSS. An SDSS consists of:

- a spatial database containing all data, spatially referenced, used in the decision process. Shim et al. (2002) explain the necessity of the interchange of this database via the internet and foresees the development of SDSS interacting via data exchange,
- scientific models using and producing data,
- a toolbox containing features from a geographic information system and further tools that enable the system to analyze and interpret the results, and
- the Graphical User Interface (GUI) connecting the user and computer system.

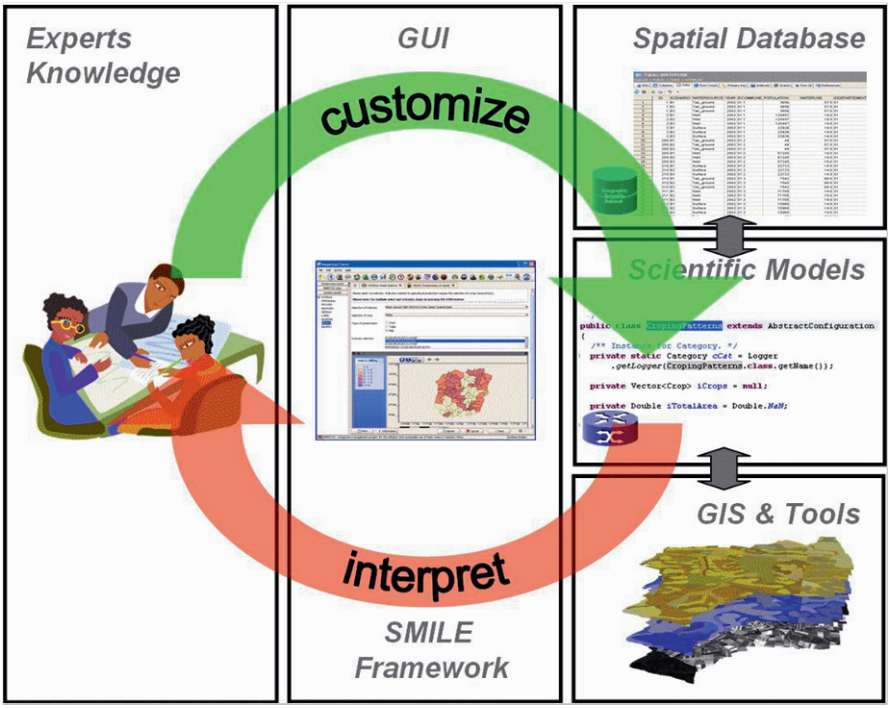

Fig. II-2.2.1: Communication diagram of the decision support process (Source: modified from Hahn 2001).

Uran and Janssen (2003) and Shim et al. (2002) focused on a group of experts who are able to customize and configure the system, to interpret the results and to maintain the system. A Decision Support System is often seen as a pure computer system proposing the right decisions to make. As mentioned in Ochola and Kerkides (2004), decision support is neither a decision proposal nor a decision itself. Rather, it aims to give the decision-maker more solid and efficient information in the target domain of the SDSS in the most comprehensible way possible (Hartley and Almuhaidib 2007).

Information Systems (IS)

Information Systems are, like DSSs, interactive and adaptable computer based systems. They do not contain scientific models and, therefore, are not able to create new user defined dynamic scenarios or simulations.

Nevertheless, they provide information about data, predefined scenarios and simulation results. Within the IMPETUS SDSS (ISDSS) framework, information systems are also used to present the results of complex simulation models in

cases where high demand on computer resources prevents direct application. Additionally, information systems are implemented to enable a deeper understanding of the applied data; for example in the domain of climatology, where data must be pre-processed using a complex modeling chain, data is presented in an IS before being used in hydrological models.

Monitoring Tools (MT)

The highest level of interactivity and adaptability is implemented in monitoring tools. They include all functions of SDSSs and, additionally, the ability to integrate recent data. The monitoring tools aim to inform users about the current state or near-future consequences of current developments. As presented in detail below, the MT PRO-RES (PROgnosis of snowmelt runoff for a water REServoir) estimates the available water resources during summer by taking the snow cover of a mountainous region and precipitation during the winter season into account. Like in an SDSS, it is possible to analyze possible future developments by calculating different scenarios.

Compilation of requirements

The developer of a Spatial Decision Support System has to take into account a number or requirements that are requested by different target groups. A literature review shows that these requirements are often not named explicitly. Generally, system developers define their views on DSSs and SDSSs without arguing for what is demanded by the target group, the scientific discipline or the societal circumstances. According to Uran and Janssen (2003), this is one of the main reasons why DSSs are often not used or maintained after the end of a project.

In the following, an explanation of the requirements that the implemented systems must satisfy from different point of views is given. They are:

- project aspect: What are the requirements regarding the individual aspects of decision support from the IMPETUS project point of view?
- general aspect: With which requirements is an SDSS confronted in general?
- organizational aspect: What do we need to successfully implement an SDSS and who must be involved? What is the appropriate communication structure concerning the development and implementation of the system? How can this communication be supported?
- societal aspect: What is the demand of the users – who is the target group?
- scientific aspect: Which functions are needed for different systems? Which functionality assures scientifically correct preparation, implementation and presentation of the systems?

- technical aspect: What are the technical standards to be fulfilled? Are there specific technical requirements of the target group that must be taken into account?

Project aspect

At the beginning of the implementation phase of IMPETUS, scientists and project leaders planned to develop about 30 different SDSSs, ISs and MTs dealing with water related management problems. Because of the development of different systems, a broad diversity of requirements needed to be considered. Four examples of the technical requirements and their applications within the IMPETUS SDSS are shown. Many other systems are mentioned and discussed in other parts of this book.

The need to create individual systems was combined with a scientific approach to integrate different systems into one software platform. The target groups of the systems were varied in all conceivable ways. Moreover, the time available for development was short (max. 2 years) and the number of developers was limited. These constraints lead to the need for an effective development procedure of the systems.

General aspect

A general requirement is the implementation of decision trees to give users and decision-makers an overview of the decision process. In a decision tree, the decision process is divided into logical steps, which provide an easy insight into the complexity of the DSS.

Decision making in a DSS is supported by creating, analyzing and comparing alternatives – in an SDSS this is done in geographically referenced way. From a scientific point of view, these alternatives are called scenarios (see chap. II-3), if they are designed to allow analysis of possible future events through consideration of alternative possible outcomes. The SDSS has to support the development and application of different scenarios with a multi-criteria decision support technique (Jankowski 1995; Seffino et al. 1999). More specifically, it is necessary to be able to evaluate the outcome of different parameterizations of the system (scenarios) in comparison to a baseline scenario. According to Shim et al. (2002) interchanging these scenarios via the internet would enable scientists to contribute to the problem to be solved.

Organizational aspect

A prerequisite for the successful development of a permanent, sustainable and maintained SDSS is the organizational background. Not only are qualified collaborators required, but so is an environment that supports the development and communication process. Based on Hahn (2001) and Segrera (2003), we distinguish the

different participants in the DSS process. At the development level, there are the scientists, the system developer and the software developer. Furthermore, the DSS architect must adjust the requirements to fit the needs of the users, stakeholders and experts (see fig. II-2.2.2). In addition, the ability of members to communicate, interface and collaborate in the process (see 'societal aspect') is indispensable.

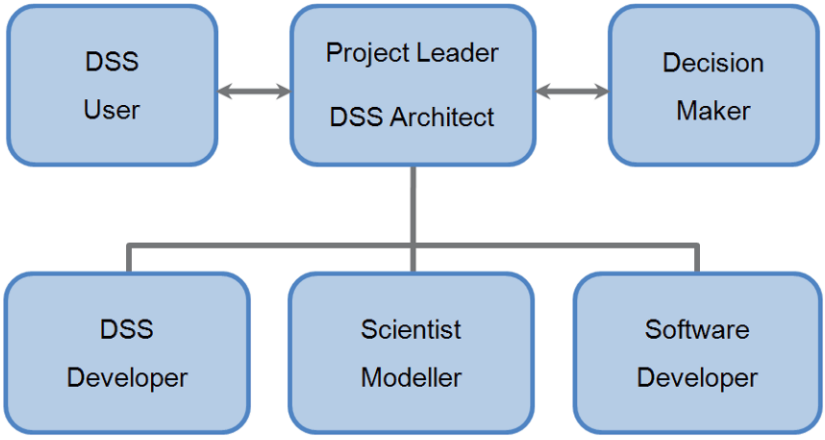

Fig. II-2.2.2: Organisation chart of the participants in the DSS process.

In most projects, DSSs or SDSSs use existing results that are chosen by the DSS architect or the project leader. Therefore, communication between users and DSS architects or between project leaders and decision-makers is of utmost importance for a successful design (Uran and Janssen 2003). While the communication at the development level can easily be supported with the help of software tools, at the political level it requires more personal care.

In general, it requires sufficient time and budget to build subsequent versions of the prototypes of the system. A successful prototype will further increase the end-user commitment and eventually trigger further investments in the DSS development. To be realistic, there is nearly always a requirement to develop the system "on time", which is often too short.

Societal aspect

Societal aspects are concerned with the social interrelations and the soft skills in the decision making process. The necessary motivation of all members taking part in the decision process can be supported by highlighting the advantages of the decision support. Provisos and interventions of all participants have to be taken seriously, especially those from other disciplines, hierarchical statuses or cultural backgrounds. This will influence significantly whether a DSS is used or

not. Many requirements have to be adapted to the different target-groups.

- Systems have to consider the skills of the user,
- the different roles of the involved persons in the decision process such as customizer, user, translator, or developer (Hidalgo et al. 2007). These roles might be distinguished by knowledge, duty in the process, discipline or support requirements,
- different regional settings that also include ethnical background, and
- available computer resources. For example in rural areas, the system should also be able to produce hard copy output of the results (Ochola and Kerkides 2004).

There is an additional aspect that is often ignored: the license cost. Universities often have special contracts for highly sophisticated software packages. Users in other organizations do not have this advantage and are often unable to pay the license fee. The cost, then, would be an important handicap for using the systems. Therefore the requirement is broadened to use software without licensing fees as much as possible and to enable users to use free operating systems like Linux®. However, this goal is not always feasible.

A general requirement from a societal point of view: a DSS process always needs the early involvement of the end-user in the development process and its application. It is further necessary to inform interested people about the decision process and its results (Giupponi 2007). This balances different and contradictory demands.

Scientific aspect

A scientific SDSS has further requirements. For example, there is the integrability, exactness and quantitative character of scientific models or the necessity to integrate geo-referenced data or to perform remote sensing. The scientific requirements increase with increasing complexity of the systems. For IMPETUS, the main effort is to integrate different disciplinary scientific models that can be loosely coupled (Christoph et al. 2008). This means that the result of one system may be used as the input or configuration of another system. Because these results can be in very different formats, times or geographical scales, easy to use but powerful interfaces must be developed. The design of the system should additionally enable the use of deeply coupled modeling in order to enable it work with the most effective and ambitious coupling types (Matthews et al. 1999).

Scientific SDSSs have a great demand for documentation (Seffino et al. 1999). The system must be able to support functionality that gives detailed information about the input data, the decision process, integrated models and parameters, and the reliability and significance of the results.

Technical aspect

Driven by organizational, societal and scientific aspects, many technical requirements of an SDSS are pre-assigned. Additionally, standards in software development exist that have to be considered. The known standards in software development are manifold. They are all motivated by the need to be efficient in programming, functional in runtime, easy to learn and maintain for users, and top-performing. Only some of the most important concepts should be mentioned here:

- the OOP – Object Oriented Programming
- a framework design (see below)
- the separation of logical parts
- the use of a relational database and geo-database
- the use of GIS – Geographical Information System
- the use of a form-based GUI
- the implementation of pipeline technology
- the use of special standardized languages like java®, XML(extensible markup language), etc.

Table II-2.2.1: Contradictions in the requirements to an efficient SDSS.

Autonomy of a system	Integratibility of systems
Simple manipulation of data and parameters	Complex functioning
Flexibility in function and caonfiguration	Simplicity in development
Reusability	Individuality of solution
Good usability	Diversified actions possible
Fast development	Sophisticated function
Licence fee free software	Recent top-level features
Usable via internet in server mode	Standalone for Users without internet
Usable with weak pc-environment	Good performance in complex models

II-2.3 The Scientific Model Integration pipeLine Engine Framework

The SMILE (Scientific Model Integration pipeLine Engine) framework is a development platform for SDSSs, ISs and MTs designed to meet the requirements outlined above. This software framework (DocForge Programming 2003) aims to facilitate software development by allowing SDSS developers to spend more time meeting SDSS requirements and less time dealing with low-level details of providing a working system. Software frameworks are well known in DSS devel-

opment (Ma 1995; Becker 1999; Riehle 2000; Gachet 2003; Morley 2004), while the definition of the term 'framework' is even more heterogeneous than the definition of DSS. Often the term 'DSS Generator' is used for the same tools (Sprague 1980; Segrera 2003). Lautenbach et al. (2009), Rizzoli and Young (1997) and Denzer (2005) state that the development of DSS frameworks is an important and necessary step for the future of decision support evolution.

Before discussing which requirements are met by the SMILE framework and how it does so, a detailed view of the process, architecture and functionality is provided.

Structure of the SMILE framework

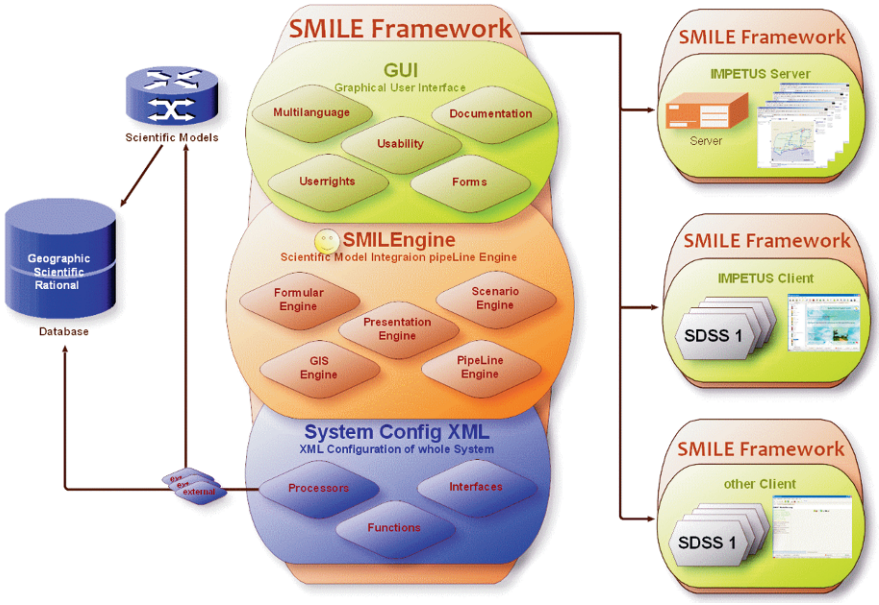

Fig. II-2.3.1: Component based structure of the SMILE Framework.

The framework (see fig. II-2.3.1) contains all the modules for accessing database and scientific models, performing geographic operations, and presenting results that meet the requirements of an SDSS. The framework is designed to be used in different environments and projects with completely different conditions. For implementing an SDSS, it is not necessary to use the development language java® because XML is used. The SMILE framework also incorporates a server-based version that is compatible with the standalone client version.

GUI: Graphical User Interface

The user interface is designed to be both easy to use and secure in data management. The system developer can specify the exact constraints of the parameterization needed. The functionalities allow the user to have both simplistic use and complex functionality (see fig. II-2.3.2). Forms are created by arranging different form components into one view. All components are able to directly react to each other's changes. The created data is forwarded to the pipeline (see below) using java object design that transports from one component to another. The documentation is directly linked to the functionalities. One can choose between documentation resources on the internet, in the form of pdf or in integrated html. The user has the ability to browse the IMPETUS Atlas application (http://www.geopublishing.org) via a fully integrated browser in SMILE framework that provides geo-referenced maps. The implemented user rights module controls all user role related tasks. It can ensure that the user only has access to elements for which he is authorized.

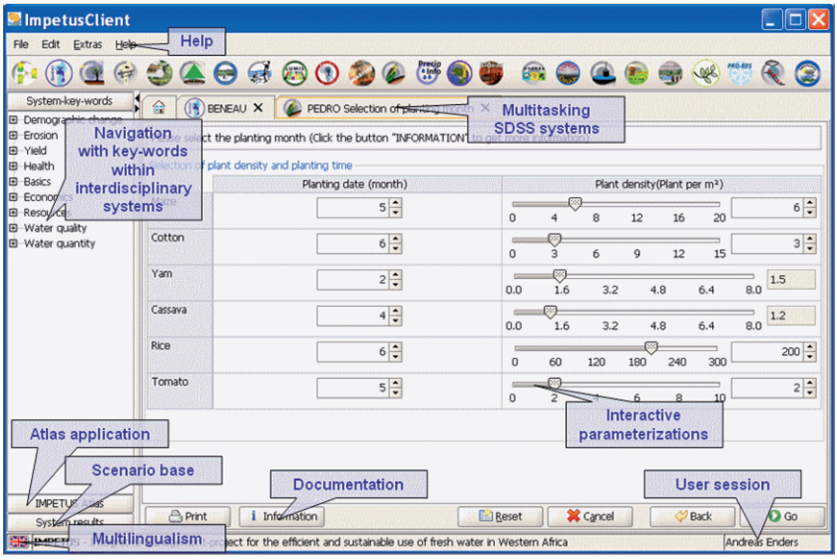

Fig. II-2.3.2: GUI of IMPETUS Client created with SMILE Framework.

Finally, the GUI is enabled with the java standard multilingualism concept. Therefore, the logic component is isolated as well. All parts of the software can be localized using this feature, if it is requested by another participant in the development process.

Altogether the SMILE framework contains an environment for customizing a target-group specific and easy to use GUI prepared for the SDSS development. Despite the powerful technical sophistication, the main focus of the SDSS framework remains usability for the end user.

SMILEngine: Scientific Model Integration pipeLine Engine

The SMILEngine is the core of the framework. It combines features for automating the decision process without impairing the possibilities of user interactions. The formula engine provides interactive transportation, printing and data availability; the GIS engine supports the systems with sophisticated GIS features; the scenario engine provides the system with a built in library of results for comparison; the pipeline engine controls the step by step organization without eliminating possibilities of multitasking and parallel computing; and the presentation engine presents interactive results in the form of diagrams, tables, maps, html or pdf.

Configuration XML

The client configuration XML enables the SDSS developer to easily develop a system without much knowledge of programming languages. He can configure whole systems in accordance with the SMILE specific grammar using XML standards.

Based on our experience of the IMPETUS project, a normally skilled scientist can develop his own simple SDSS or IS after a short training period. The grammar of the XML configuration can be automatically checked ensuring correct code grammar.

The implementation of extended features like external models, new form components, functionalities or background processors is possible by overwriting an abstract class. Besides the core featured Geotools framework, the ArcGIS Engine (ESRI®) has been incorporated by Laudien (2008c) in this way. The implementation of scientific models is possible in various prepared ways that generally only demand XML configuration:

1. Integration is achieved by interfacing the configuration, execution and import of results – mostly for software written in FORTRAN, PASCAL, etc. The analysis of results is achieved with the help of the integrated rational database Hypersonic SQL (Toussi 2008).
2. Integration using Excel® (Microsoft Corporation) as data source and/or model implementation.
3. Full integration by creating SMILE Processors interacting with the Hypersonic SQL or native implementations.

With this integration technique, there are a great number of pre-existing background processors like file system management, database management, GIS, ASCII-file management, Excel® spreadsheet management and model management. There are interfaces created for the models CLUE-S (Verburg et al. 2002), EPIC (Williams et al. 1983), GAMS (Dellink 2007) resp. CAPRI (Britz et al. 2007), PESERA (Tsara et al. 2005), SAHYSMOD (Oosterbaan 1998), SRM (Rango and Martinec 2000), SWAT (Arnold and Fohrer 2005), CROPWAT (Smith 1992), and UHP (Bormann and Diekkrüger 2004).

The IMPETUS SDSS which is based on the SMILE framework is available at http://www.impetus.uni-koeln.de/en/isdss.html and from the authors. It contains the components discussed before and some of the implemented Spatial Decision Support Systems (see sect. II-2.4). As the SMILE framework is a public domain software it can be used for developing specific SDSS, MT or IS.

II-2.4 Examples for Spatial Decision Support Systems, information systems and monitoring tools

The aim of implementation of the SDSSs, ISs and MTs is in general to transfer knowledge, data and models to the partners so to support decision making processes in the field of water related problems. While it is not possible to present all 30 systems, we focus on the following four systems:

- PEDRO (*Protection du sol et durabilité des ressources agricoles dans le bassin versant de l'Ouémé Supérieur*): SDSS for estimating erosion and crop production at the regional scale using the integrated models SWAT and EPIC
- IWEGS (Impact on Water Exploitation on Groundwater and Soil): SDSS for analyzing water demand and water availability in an oasis environment considering salinization by integrating the models BIL(Groundwater balance model), CROPWAT, CROPDEM (crop water demand), SAHYSMOD
- PRO-RES: Monitoring Tool for analyzing water storage and snow melt of mountainous environments using satellite images and the model SRM (Snowmelt Runoff Model)
- LISUOC (Livelihood Security in the Upper Ouémé catchment): IS on livelihood security regarding demographics, work (production, consumption, and distribution), capital, risk strategies, and health

II-2.4.1 Spatial Decision Support System PEDRO

The sub-humid savannah of Benin is characterized by fast demographic growth, including migration from the densely populated southern regions and the resource scarce Sahelian zone. This development puts high pressure on the natural resources and is reflected in high deforestation rates, loss of soil fertility and conflicts concerning water and land. On the other hand, food production must satisfy the growing population. Future Climate Change may aggravate the problem. National and local authorities are interested in balancing concerns of security and economic development without compromising the natural resource base.

The SDSS Pedro has been developed to assist decision makers in identifying strategies to improve food security without compromising natural resources.

Aim of PEDRO

The objective of the SDSS PEDRO designed for the Upper Ouémé valley, Benin, is to assess the combined effects of changes in climate, land use and crop management specified by the user along the following target indicators:

- annual and monthly discharge from 121 sub-catchments,
- annual sediment load from 121 sub-catchments,
- soil erosion,
- crop yield and biomass production of major crops, and
- nutritional value of food production.

Application

The large range of target indicators requires the application of two complementary models: the hydrological and erosion model SWAT and the agro-ecological model EPIC (fig. II-2.4.1). The semi-distributed hydrological model SWAT is designed for the regional sale (Soil Water Assessment Tool; Arnold et al. 1998) (see sect. I-6.1) while the agro ecosystem model EPIC (Environmental Policy Integrated Climate, Williams et al. 1983) (see sect. II-4.1) is linked to the land resources information system SLISYS-Ouémé (Soil and Land Resources Information

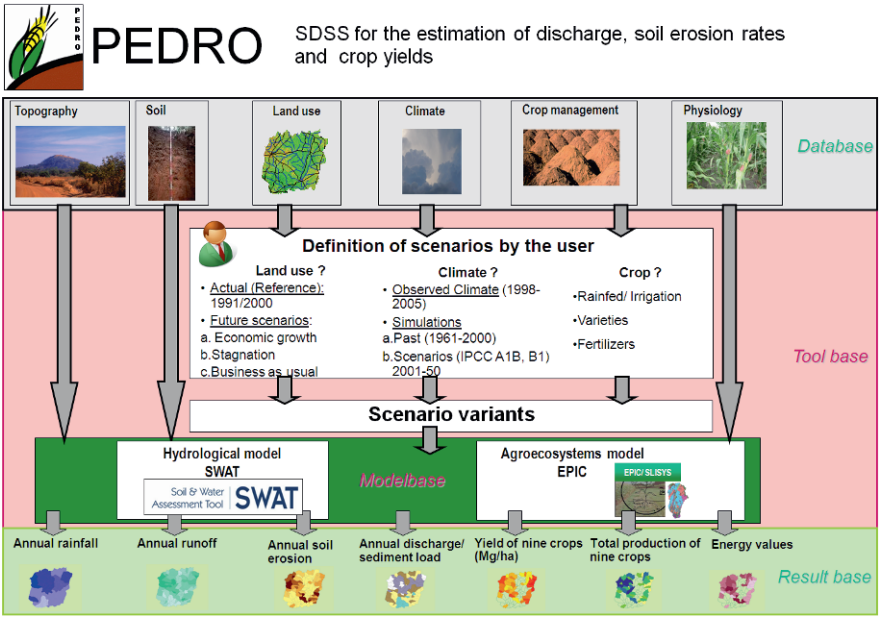

Fig. II-2.4.1: The components of the SDSS PEDRO.

SYStem) is applicable on the field scale. Both models compute similar processes, but with different approaches and on different scales. In PEDRO, the first three indicators are calculated by SWAT, whereas the last three are calculated by the EPIC model. Soil erosion is calculated by both models, but due to the scale problem only SWAT is able to consider depositional processes. The output is either the mean value over the entire basin or over the 121 sub-catchments (see fig. II-2.4.2). The SDSS PEDRO is composed essentially of four components: (1) the database (2) the user interface (tool base) (3) the numeric models (model base) and (4) the database of the output (result base) (see fig. II-2.4.1).

The input database contains the specific data necessary to run the two simulation models SWAT and EPIC. With the use of forms, the user can select a combination of input data (e.g. meteorological time series or different land use scenarios) as well as the duration of the simulation. This input can be combined with different management options to be defined by the user. The combination of a meteorological time series with a land use scenario and certain crop management options constitutes a 'combined scenario' or 'scenario variant'. The scenario variants determine the boundary conditions for the model simulations. The output of the simulations is then transferred to the result database and can be retrieved by the user through the interface as tables, figures or maps. The simulations are based on a number of input data such as topography, soil properties, climate, land use, crop management, and crop parameters.

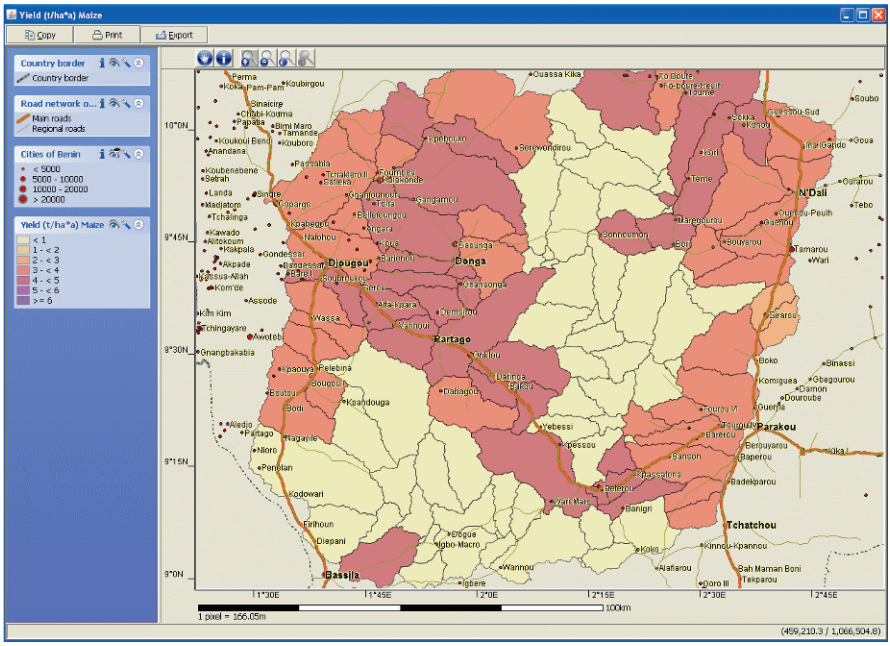

Fig. II-2.4.2: Subdivision of the catchment to be covered by the SDSS PEDRO.



Fig. II-2.4.3: Form functionality in the SDSS PEDRO to define rate and timing of mineral fertilizer application.

The system offers the choice to either select a predefined or to newly define a set of parameters concerning climate, land use and crop management. The user configures the system with a series of forms within the form engine of the SMILE framework. The parameters for the model simulations can be defined by the user and made available to the model through the pipeline engine (see fig. II-2.4.3).

The user defines scenario variants that are a combination of climate and land use scenarios, selection of crop varieties, irrigation type, irrigation frequency, water availability for irrigation, planting month, planting density, fertilizer timing and application rate. Theoretically, about 3000 combinations are possible for e.g.

maize cropping. Therefore, after having defined a specific combination of options (scenario variant) the user must label it with a unique scenario name. In addition, he should provide a detailed description of the scenario variant.

The model simulations are controlled by the SMILEngine. It guarantees that the simulations for the user-defined scenario variants are carried out in a sequential order. After each running of the simulation, selected output variables are automatically extracted from the model output files by a java-coded wrapper and transferred into a fully java compatible SQL database (HSQLDB). Then the simulation of the subsequent scenario variant will be performed. Finally, the results are transferred into the scenario database.

Results

After finishing the calculations of the defined scenario variants, the user is forwarded to the result section of the IMPETUS SDSS client. The user can retrieve the results related to the target variables (see above) via the user interface.

In view of the large quantity of output parameters, the interface presents mean values over several years (often per decade) (see fig. II-2.4.4). First, the user can select the desired indicator in a combo box. If the indicator is related to agricultural production, he should select the preferred crop in a second combo box. Then

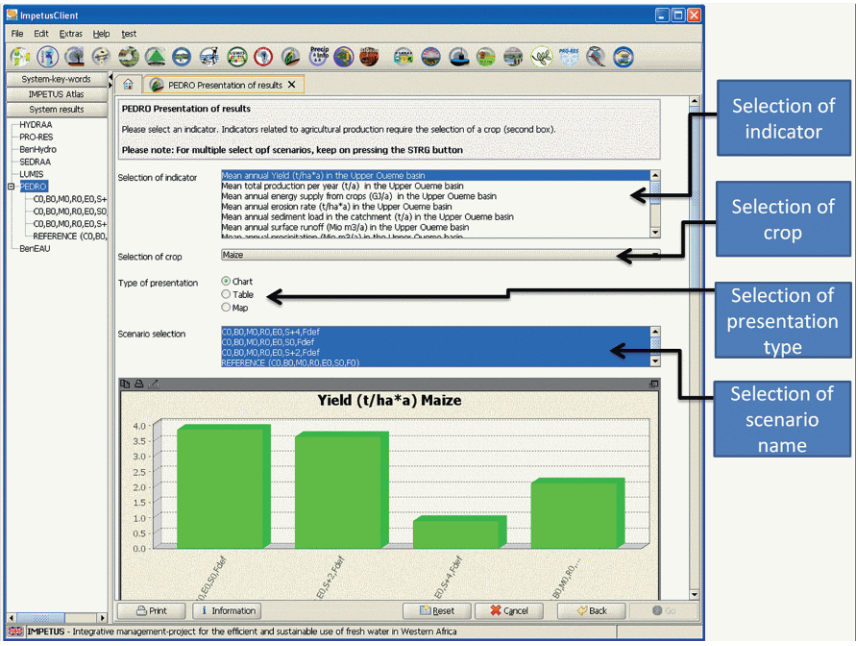

Fig. II-2.4.4: Selection of scenario variants and their target indicators in the results database of the SDSS PEDRO.

he can choose between three types of presentation options (figures, tables, and maps). The option 'Map' can only represent one scenario at the same time, whereas for the other presentation types the results of several scenarios can be displayed simultaneously. Nevertheless, the user is able to open numerous maps for comparing the results.

The map presentation can be enriched with additional spatial layers of the IMPETUS Atlas, which facilitates the localization of objects on the maps. This is performed by opening the IMPETUS Atlas in the explorer window on the left hand side of the main window and moving the desired layer by a 'Drag and Drop' action from the atlas into the map window, which shows the results of the simulation.

Discussion

From the scientific point of view, the PEDRO system is very complex. Combining different models with different aspects of the natural environment is very challenging. PEDRO manages the complex procedure of these coupled models very transparently and therefore provides selectable options to the decision makers.

The matter of reliability is checked and explained in the documentation component. Because central questions can be answered and alternatives can be modeled, the system provides a broad spectrum of decision support.

II-2.4.2 IWEGS

The SDSS IWEGS (Impact of Water Exploitation on Groundwater and Soil) focuses on recommendations concerning ground water availability and soil salinization derived from six oases in Morocco. Because it is based on a complex logical decision tree and the loose coupling of four existing models, this SDSS was predestined to be presented as an example.

The model C.E.M. Drâa (*Consommation d'Eau Ménagère*) estimates the annual domestic water consumption per oasis by considering observed demographical trends. CROPDEM presents a look up table, which is based on the model CropWat (Smith 1992). Thus, the annual water demand of the major crops is assessed for each oasis. The annual volume of available groundwater for each oasis is calculated by the model BIL, based on the groundwater budget estimation. By using the SDSS coupling approach, the models C.E.M. Drâa and CROPDEM pass their results on to BIL as negative items in the groundwater balance. Thus, the crop water demand is set to equal the minimum irrigation amount, which is extracted from groundwater. In addition to the three MS Excel based models, the FORTRAN model SahysMod is also connected and implemented into the decision processes of IWEGS. For further information concerning the models see section I-6.2.

This contribution focuses on the development and implementation of non-Java based interfaces that couple pre-existing Microsoft® (MS) Excel-based models to an individually designed SDSS. The applied methodological approach is embedded within the SDSS IWEGS. To access MS Excel files within these developed systems, Java API POI-HSSF (by Jakarta) was used. HSSF provides a way to create, modify, read and write Excel-based spreadsheets without relying on the Excel-software itself. Additionally, this library supports cell-functions and formulas.

Application

Based on the state-of-the-art software development design approach MVC (Model-View-Controller), the interfaces are developed as framework processors (see before). To meet the given requirements of accessing MS Excel, three processors are programmed: (i) *getXLSValueProcessor*, (ii) *setXLSValueProcessor* and (iii) *RecalcXLSProcessor*. Each of these processors connects the SDSS to the *.xls -file, accesses a specific spreadsheet and uses the defined cells within that sheet. With these processors, it is possible to access and run complex Excel-based models from a user-friendly SDSS-Graphical User Interface (GUI) by (i) providing the given input parameters from the Excel cells, (ii) allowing the editing of the parameters in the SDSS-GUI, (iii) permitting a recalculation and simulation of the model irrespective of the SDSS, (iv) retrieving the processed outputs from the model and finally (v) visualizing them.

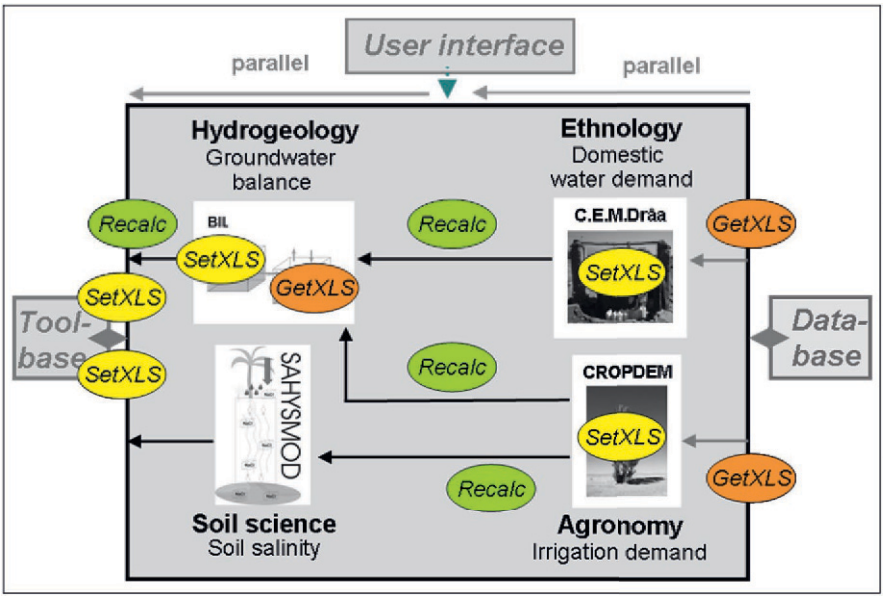

Fig. II-2.4.5: Flowchart of the IWEGS methodological approach (Source: modified from Klose et al. 2008; cf. Laudien et al. 2008a).

In order to assess the impact of water exploitation for domestic and agricultural purposes on groundwater availability and soil salinity, the coupling of different disciplinary methods and existing models was realized within the development of IWEGS (see sect. II-5.2 for further details). This interdisciplinary approach leads to parameter optimization of the input for the models BIL and SahysMod. By coupling the models, C.E.M. Drâa and CROPDEM pass their results to BIL in order to optimize the negative items in the groundwater balance, such as domestic extraction and irrigation withdrawal (see fig. II-2.4.5). With respect to scenario projections, the coupling of the models needed to be done dynamically. Consequently, the interfaces between the MS Excel-based models and the SDSS are essential and need to be developed modularly.

In addition to this modular model coupling approach, figure II-2.4.5 also shows where interfaces of pipeline processors are implemented into the overall SDSS development approach. Based on the existing models stored in the IWEGS geo-database, the *getXLSValueProcessor* provides the model input parameters of the Excel cells. With a developed SDSS-GUI, the user is able

1. to edit these parameters and rewrite them back into the sheet (*setXLSValue-Processor*),
2. to recalculate and run the model irrespective of the SDSS (*RecalcXLSPro-cessor*),
3. to retrieve the processed outputs form the MS Excel sheet and
4. to visualize them in the SDSS-GUI *(getXLSValueProcessor*).

By having the option to modify pre-defined parameters (or boundary conditions), the IWEGS users are able to create scenarios on their own. Thus, the GUIs enable the convenient handling of a complex system and, from a technical point of view, guarantee error-free model-simulations.

Based on the predefined structure of an IMPETUS SDSS, after accessing IWEGS from the IMPETUS client, the start screen and flowchart provide information about the system and show its structure (see fig. II-2.4.6a & b). Once the climatic scenario is chosen, the first model (C.E.M. Drâa) is initialized using the *getXLSValueProcessor*, which fills the default model input parameters into the given GUI table (see fig. II-2.4.6c). By using the IMPETUS framework form components, the user is able to edit these default values directly at the GUI. In the next pipeline step, the *setXLSValueProcessor* writes these values back into the Excel spreadsheet and therefore provides C.E.M. Drâa user-defined model input parameters. Finally, the *RecalcXLSProcessor* runs the model and again provides the output cell values to the *setXLSValueProcessor* for sending model connecting parameters to other models. In addition, the output cell values feed the *getXLS-ValueProcessor* for visualizing the output at the GUI (see fig. II-2.4.6d showing the GUI of CROPDEM).

To generate the spatial decision support in terms of an interactive GIS, predefined thresholds are used to approximate the groundwater stock and soil salinity results and to generate classified thematic maps. Subsequently, the GIS results

(soil salinity and groundwater volume) are displayed (see fig. II-2.4.6e), including the possibility of displaying time series (histograms), by using the ArcGIS Engine. In addition to the GIS output, the table output forms (see fig. II-2.4.6f) provide the annual household and agricultural water demands, the groundwater salinity, -efficiency and -sufficiency.

To summarize, the SDSS IWEGS, with its implemented POI HSSF connecting and accessing processors, can be used as a comprehensive spatial decision support tool for specific stakeholders in the Drâa oasis region in Morocco (Laudien et al. 2008a). Consequently, IWEGS can be used to provide decision support with regard to (i) further investigations and measures on groundwater availability and soil salinity, (ii) climatic change influences, as well as (iii) how management options influence the state of the groundwater and soil resources.

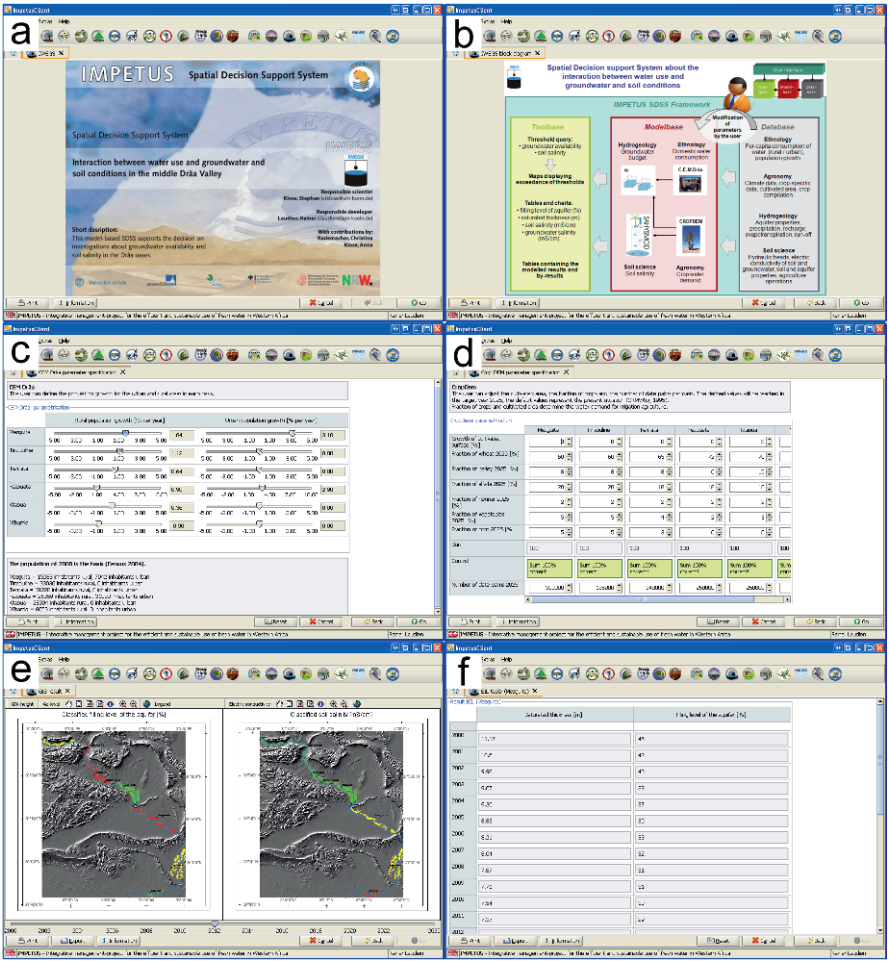

Fig. II-2.4.6: IWEGS screenshots of preliminary SDSS development results: (a) start screen, (b) flowchart, (c) C.E.M Drâa GUI, (d) Cropdem GUI, (e) GIS output, (f) table output.

II-2.4.3 Monitoring tool PRO-RES

Snow in the High Atlas Mountains is a major source for freshwater and for water availability in the semi-arid lowlands of south-eastern Morocco. Snow accounts for between 20 to 80% of total precipitation at the IMPETUS test sites in the M'Goun region (Schulz and de Jong 2004; Schulz 2006). The ultimate aim is to forecast available water for irrigation from the recent snow coverage.

To cope with this dynamic situation, the snow cover was analyzed through space and time in three ways: remote sensing, ground measurements of snow and weather characteristics, and snowmelt modeling.

Aim of PRO-RES

As mentioned in the introduction, an IMPETUS MT is defined as an SDSS with the ability to analyze recent data to simulate future scenarios. The following two questions should be answered by the decision process:

1. How does climate change influence the snow storage and inflow to the reservoir Mansour Eddahbi (Ouarzazate, Morocco)?

This question focuses on the long-term development of water availability in a regional context. The future amount of snowfall and precipitation in the High Atlas and the valley of Ouarzazate are estimated by climate scenarios. Changes in the hydrological cycle driven by changes in the climate scenarios are modeled with an SRM (Snowmelt Runoff Model; Rango and Martinec 2000) (see sect. I-6.2). The inflow and filling level of the reservoir are calculated by the MT PRO-RES (*PROnostic de la fonte de neige pour un barrage REServoir; PROgnosis of snowmelt runoff for a water REServoir*).

2. How much water is stored in the snow pack that will fill the reservoir in the coming months?

Answering question 2 requires data about recent snow cover and an estimation of the weather conditions for the following months. Within PRO-RES, recent field and satellite observation data is combined with statistical weather forecasts and the snowmelt runoff model SRM. Results will calculate the inflow to and filling level of the reservoir. The use of recent data provides the decision-maker with more reliable results.

Application

The system PRO-RES is implemented in the SMILE framework using standard features and specialized modules (see fig. II-2.4.7):

1. Management and treatment of MODIS satellite images with standardized remote sensing processors (see fig. II-2.4.8),

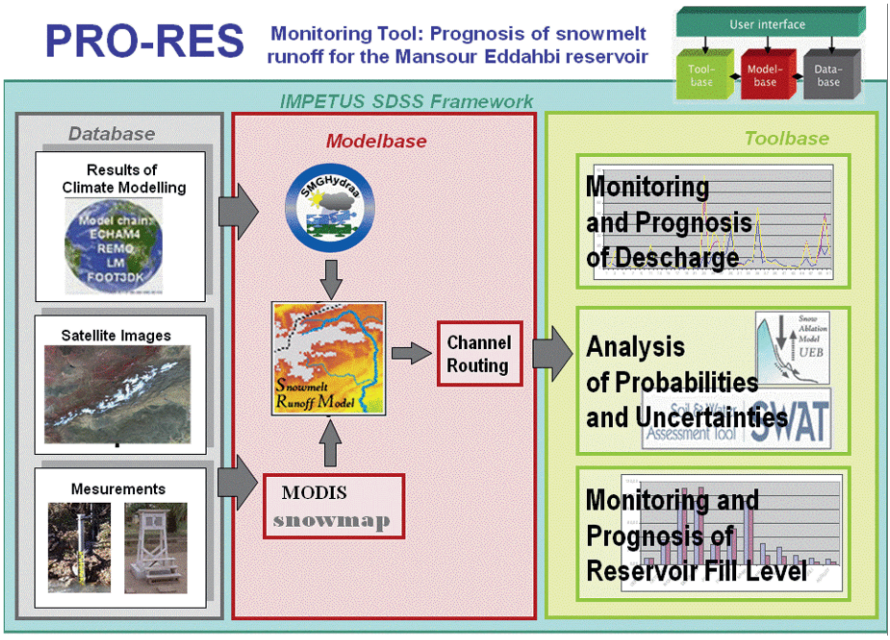

Fig. II-2.4.7: Structure chart of the PRO-RES Monitoring Tool.

2. management and transformation of climate data taken from field observations and climate simulation from the integrated SDSS SMGHydraa (Statistical Model for the Generation of Climate Data for Hydrological Applications in the Drâa Region; see sect. II-3.2) using resultant model data as input for PRO-RES (loosely coupled),
3. creation of user-defined scenarios using the form (see fig. II-2.4.9) to change parameterizations of the system and the model,
4. calculation of snowmelt and discharge with the fully integrated and therefore database driven model SRM, and
5. presentation of the result data using standard FormEngine features to analyze and compare different scenario simulations incorporated.

PRO-RES uses the satellite image product MOD09 (USGS) of the MODIS sensor on the Terra satellite to recognize snow covered areas in the High Atlas Mountain area. The MODIS satellite images are available free of charge (NASA 2009). Figure II-2.4.8 shows the automatic process of MODIS integration with PRO-RES. After a first quality check of the offered images and download via ftp, the image is uploaded into the system. The image is then treated using predefined standardized SMILEngine processors. First, the image is re-projected and clipped. Via NDSI (Normalized Difference Snow Index) the raster points with a significant snow cover are identified. The intersection with the digital elevation model (DEM) results in the size of the snow covered area for each elevation

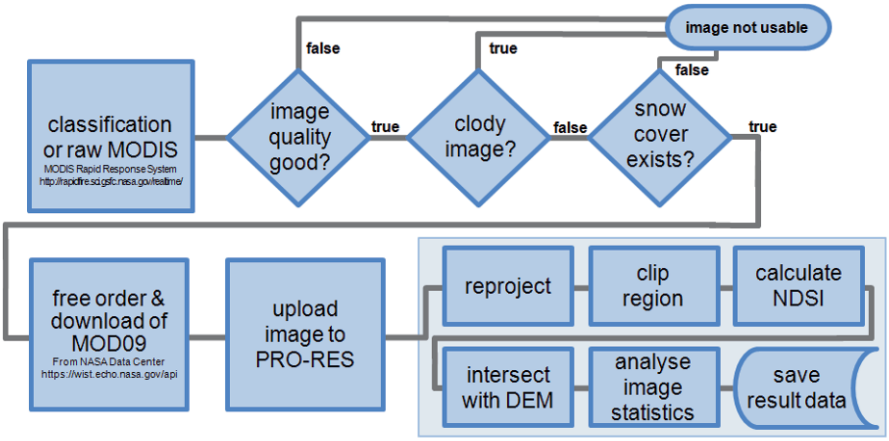

Fig. II-2.4.8: Enchained steps of the use of MODIS satellite images within PRO-RES with application of standardized SMILE processors.

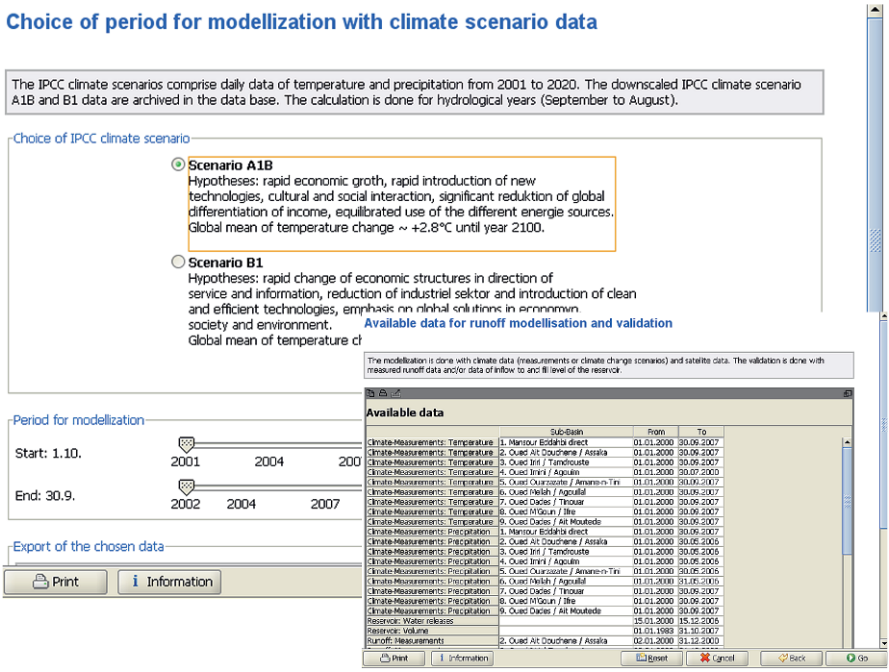

Fig. II-2.4.9: Interactive forms showing selection of climate scenario for the SDSS PRO-RES.

level. The recent satellite image treatment adds actual data to the system's database composed of MODIS imagery since the year 2000.

The PRO-RES MT uses both satellite imagery and climate data from field observations (where they are available) for the past and variable climate scenarios. This weather information has to be generated using scientific methods. Due to high demand concerning disc storage and computer resources, a special technique was applied. The normal process of downscaling by applying the meteorological model chain is very complicated. Therefore, the system PRO-RES uses the result data of the SDSS SMGHydraa (Statistical Model for the Generation of Climate Data for Hydrological Applications in the Drâa Region; see sect. II-3.2) that is integrated into many Moroccan SDSSs. SMGHydraa is used to generate meteorological-climatic data by interpolating climate model simulations and applying a statistical downscaling method. With the integration of SMGHydraa into PRO-RES, the user has the possibility of modifying the climate scenario parameters to generate weather data applicable for PRO-RES.

The easy-to-use, form-based questionnaire enables the user to create his own individual scenarios. If the user is a specialist, he is able to further modify the complex parameterization of SRM. Normal users who do not have such capabilities will be provided a form with a limited amount of parameters to vary.

The simulation of SRM is executed as a background process within the SMILE framework. The integration of the java version of the model (Kleindienst and Baumgartner 1999) facilitates the configuration, running and analysis of the results. The data structure of the model is integrated into a relational database. While the SRM only simulates one year in one sub-basin, the MT PRO-RES is enhanced to calculate and visualize data for multiple basins and years.

The data presentation module of the SMILE framework presents the data in form of diagrams showing hydrographs or sum bar charts displaying different aspects of the results. A map view exists to compare and analyze regional differences. In order to enable the use of data in other contexts, printing and exporting is possible.

Discussion

The system PRO-RES can be used for the decision making processes within the governmental institutions in Morocco. Workshops and training sessions have been conducted to discuss the system and to guarantee the applicability. Additionally, the system could be used to facilitate scientific work using remote sensing data and the SRM. Features like the ease of implementation, the looping of automated steps, the combination of data, the configuration within a database system and the availability of interfaces made it possible to use the system for the collection and treatment of data and calibration of the snowmelt model.

II-2.4.4 LISUOC

The system LISUOC allows the user a complex but easy to operate way to query survey databases of the Upper Ouémé valley, which enables the user to find answers to key issues concerning demographics, work (production, consumption, distribution), capital, risk strategies and health quickly and effortlessly. The results illustrate, amongst others, how far the population adapts its social and economic behavior in response to external factors. For further details concerning the content of LISUOC, see section II-4.4. The software for LISUOC is structured into three main modules: (i) demographic projections, (ii) water management and institutional change, and (iii) livelihood security and resource use. This contribution focuses on the first module and presents its innovative output in terms of an interactive, multi-temporal GIS-based scenario viewer.

Within environmental and social research (as well as in several other working fields), it is necessary to calculate and visualize different scenarios before making decisions. Hence, an advanced SDSS needs to be extended by the ability to compare different scenarios. This section shows the development and implementation of a specific GIS visualization for LISUOC that enables the user to evaluate two different multi-temporal layers within one panel based on a specific SDSS as an example.

Application

Because it is implemented in the IMPETUS framework (see before), the collected data of LISUOC are stored in an ArcGIS Engine file-based geo-database. These file-based databases show a high performance when large amounts of data are involved, and there are no inherent size limits (the limit is that of the file-system itself) (ESRI 2007). The LISUOC geo-database contains:

- Survey data of 839 women and men in 640 rural and urban communes of Parakou, Tchaourou, Bassila, Djougou, Ouaké, Copargo and N'Dali (corresponding to an area of 22,260 km^2). The various subjects discussed were classified in five main subjects: work, nutrition, capital, and health as well as risk strategies.
- Digital maps and tables regarding the trends in the population development for the period between 1992 and 2025 in the seven communes of central Benin.
- A detailed database of the drinking water locations in the region including 3,300 water outlets in six communes (Bassila, Djougou, Copargo, Ouaké, N'Dali and Tchaourou).

For further information concerning the content of LISUOC see section II-4.4.

During the design process of LISUOC, detailed information about the requests, knowledge and personal needs of the potential users were already essential and

needed to be considered (Laudien et al. 2008a). Hence, by providing a multi-modular SDSS for different users, the programming of LISUOC needed to change depending on the GIS-, Remote Sensing-, and model-knowledge of the decision makers. Most of the decision-makers are experts in their research topics but have limited experience with computer technology and software concerning GISs and SDSSs. Nevertheless, the developed system should also be useable by advanced users, who have detailed knowledge of computer models and GISs, and who are able to implement additional functionalities into the decision making processes. Therefore, LISUOC had to consist of standard, as well as advanced, GIS functionalities. In addition to the implementation of such spatial analysis tools, interfaces were developed that guarantee the import and export of required geo-data.

While designing and developing question-specific SDSSs, UML (Unified Modeling Language) class diagrams help to describe the structure of the systems and can be used as programming schedules for the developer. Such class diagrams are static structure diagrams or flowcharts that show the classes of the system, their attributes and their relationships. Figure II-2.4.10 shows a simplified extraction of the UML class diagram that was developed and used for programming the multi-temporal SDSS scenario viewer named *ArcGISDoubleMapPanel*, a visual output of LISUOC.

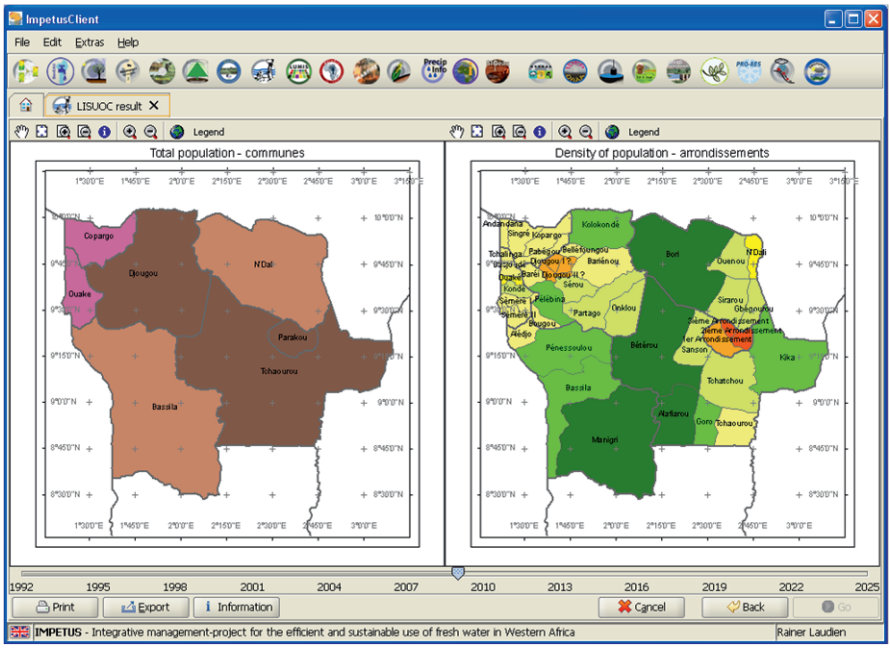

Fig. II-2.4.10: SDSS Screenshot showing the *ArcGISDoubleMapPanel* as an example. Two different vector layers (two different attributes, one time slider).

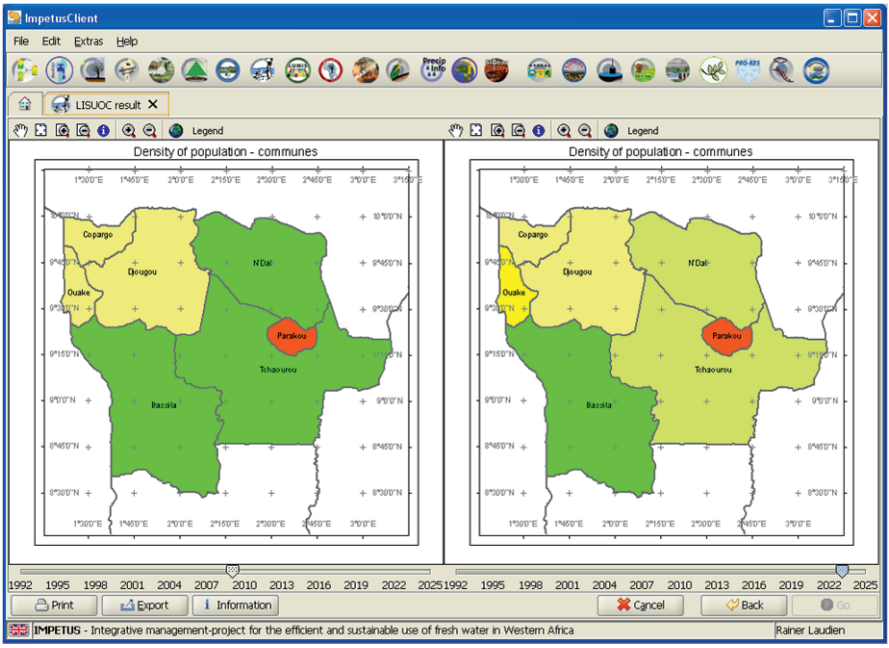

Fig. II-2.4.11: SDSS Screenshot showing the *ArcGISDoubleMapPanel* as an example. One and the same vector layer (same attribute, two separate time sliders).

The consideration of the potential user requirements resulted in several single functionalities of the *ArcGISDoubleMapPanel*. In addition to the common GIS tools integrated in the SDSS toolbar, the panel provides both thematic and non-thematic raster or vector maps, each of which contain either two different attributes and one time slider or one attribute and two time sliders (for comparison of different time stages).

Figure II-2.4.11 shows the visualization of the *ArcGISDoubleMapPanel* via two screenshots. These preliminary development results present the overall functionality of the SDSS component with feature layers as an example. Two ArcGIS Engine *PageLayoutBeans* are placed next to each other. Both of them have toolbars with common GIS tools, in addition to time sliders in order to visualize multi-temporal time stages.

By loading two feature layers of different attributes in thematic maps, the user is able to compare these two visualizations in a user-friendly way (see fig. II-2.4.11, upper screen). To meet the requirements of providing a multi-temporal scenario viewer, a Java slider component (*JSlider*) is located below the two maps. This slider has access to the multi-temporal feature layers and displays different time stages. By using a developed processor that accesses the specific time stage of the layer, the two maps of the *ArcGISDoubleMapPanel* are updated (by refresh) during run-time. Hence, the layers change their colors by moving the time slider.

Besides comparing two different attributes, there is also the opportunity to visualize the same attribute in the two maps of the *ArcGISDoubleMapPanel* (see fig. II-2.4.11, lower screen). This functionality provides an easy way of comparing two different time stages with each other in order to visualize and detect the change over the time. Each ArcGIS Engine *PageLayout* has its own time slider having the same functionality as outlined above. By showing the specified feature, the user is able to visually compare the two maps (Laudien et al. 2008b).

To summarize, LISUOC provides basic data in order to simplify the decision-making processes. The users can select a suitable combination from the subject areas (e.g., work, capital, and water management), the geographical levels (e.g., commune, water outlet) and the type of presentation (e.g., map, diagram). The results displayed on the computer screen can be printed out or exported to another document and are therefore easily used to support spatial decisions in the Upper Ouémé valley (see also sect. II-4.4).

II-2.5 Conclusions

The successful implementation of 11 SDSSs, 13 ISs and 2 MTs in cooperation with approximately 35 scientists from different disciplines show that the main requirements concerning technical, project and scientific aspects could be met, even though they are very contradictory. Various decision structures have been implemented, mostly by coupling different numerical models. The scenario base is successfully used by a number of SDSS, and therefore the development of this tool was advantageous.

Meeting the requirements concerning the societal aspect is more difficult for the DSS architects, scientists and DSS developers. Although some of the project partners were equipped with knowledge of recent computer techniques, there is still the need to balance the demand of different systems as the majority of users are poorly equipped.

Concerning the organizational aspects mentioned before, we want to widen the graph of the SDSS modules in figure II-2.2.1. Figure II-2.5.1 shows the central role of the experts in the decision-making process. An SDSS can only provide support in the domain for which the system is developed. Experts will have to perform the continual process of customizing the SDSS and interpreting the results. Evaluation, decision-making, implementation and analysis have to take place in the "real world", by taking the feedback as the next starting point of the customization process.

Within the IMPETUS SDSS, developers tried to meet the requirements as closely as possible. Nevertheless, a sustainable use of SDSSs cannot be guaranteed by the developers and project leaders. Strategies to minimize the transition effects after the end of the projects are required. To guarantee sustainable use of the systems, a close cooperation between the members of the expert group consist-

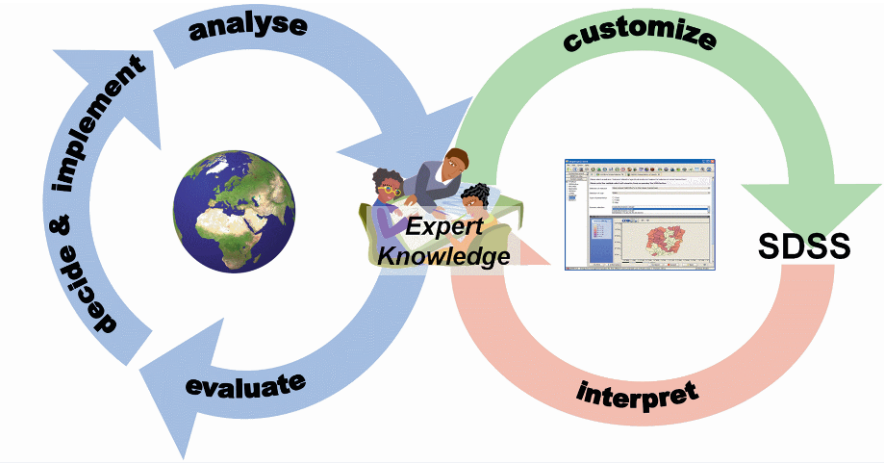

Fig. II-2.5.1: Role and duty of the expert group in the decision process.

ing of scientists, stakeholders and developing agencies is indispensable. This co-operation has been arranged during the project.

Regarding scientific decision support, at least two different approaches can be defined as given in figure II-2.5.1. Either a project could have the SDSS development as a major objective, or else a project starts by analyzing problems, collecting data and developing management options before initializing the development of the SDSS/IS/MT for knowledge transfer.

There are no general rules for which approach is more successful, because it depends mainly on the scientific knowledge about the target region. IMPETUS has chosen the second alternative because in many aspects, scarce knowledge and poor data availability were constraints in the beginning of the project and beginning immediately with development of the SDSS would have failed.

Therefore, to intensify the involvement of the participants in the second project phase, the development capacity was strengthened. Although different problems related to the organizational structures within the partner countries still exist, the application of the systems has started and positive feedback has been received. The remaining challenge is to implement the systems by training the users to train further users so that a sustainable use and maintenance is conceivable.

References

Arnold JG, Fohrer N (2005) SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrol Process 19:563-572

Becker K (1999) An Object-Oriented Frameworks-based Architecture for Decision Support Systems, CLEI Electronic Journal, Santiago-Chile. Vol.1, Paper 1

Bormann H, Diekkrüger B (2004) A conceptual, regional hydrological model fo Benin (West Africa): validation, uncertainty assessment and assessment of applicability for environmental change analyses. Phys Chem Earth 29:759-768

Britz W, Perez I, Zimmermann A, Heckelei T (2007) Definition of the CAPRI Core Modelling System and Interfaces with other Components of SEAMLESS-IF. http://www.capri-model.org/index.htm, Accessed 23 August 2009

Christoph M, Fink AH, Diekkrüger B, Giertz S, Reichert B, Speth P (2008) IMPETUS: Implementing HELP in the Upper Ouémé Basin. Water SA (online), Special HELP edition 34:481-490

Crossland MD, Wynne BE, Perkins WC (1995) Spatial decision support systems: An overview of technology and a test of efficacy. Decis Support Syst 14:219-235

Dellink R (2007) GAMS for environmental-economic modelling. http://www.enr.wur.nl/UK/gams/. Accessed 24 May 2009

Densham P (1991) Spatial decision support systems. In: Geographical Information Systems: principals and applications, pp. 403-412. Longman Scientific & Technical, Harlow, Essex

Denzer R (2005) Generic integration of environmental decision support systems – state-of-the-art. Environ Modell Softw 20:1217-1223

Gachet A (2003) Software Frameworks for Developing Decision Support Systems - A New Component in the Classification of DSS Development Tools. J Decis Syst 12:271-281

Giupponi C (2007) Decision Support Systems for implementing the European Water Framework Directive: The MULINO approach. Environ Modell Softw 22:248-258

Gosling J, Joy B, Steele GL (2005) The Java(tm) Language Specification. Addison-Wesley Longman, Amsterdam

Hahn B (2001) Towards a Generic Tool for River Basin Management – Summary of the feasibility study. Bundesanstalt für Gewässerkunde Koblenz 4:84

Hartley R, Almuhaidib SM (2007) User oriented techniques to support interaction and decision making with large educational databases. Comput Educ 48:268-284

Hidalgo D, Irusta R, Martinez L, Fatta D, Papadopoulos A (2007) Development of a multifunction software decision support tool for the promotion of the safe reuse of treated urban wastewater. Desalination 215:90-103

Jankowski P (1995) Integrating geographical information systems and multiple criteria decision-making methods. IJGIS 9:251-273

Kleindienst H, Baumgartner H (1999) Pre-operational snowmelt forecasting based on an integration of ground measurements, meteorological forecasts and satellite data. Interactions between the Cryosphere, Climate and Greenhouse Gases. IAHS-AISH publication 256:81-89

Klose S, Rademacher C, Klose A (2008) Wechselwirkungen zwischen Wassernutzugsstrategien und den Grundwasser- und Bodenverhältnissen im mittleren Drâa-Tal. In: IMPETUS Westafrika: Integratives Management-Projekt für einen Effizienten und Tragfähigen Umgang mit Süßwasser in Westafrika: Fallstudien für ausgewählte Flusseinzugsgebiete in unterschiedlichen Klimazonen, Achter Zwischenbericht, pp. 245-252. http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/IMPETUS_Zwischenbericht_2008.pdf. Accessed 23 August 2009

Laudien R, Klose S, Klose A, Rademacher C, Brocks S (2008a) Implementation of non-Java based interfaces to embed existing models in Spatial Decision Support Systems - Case study: Integration of MS® Excel-models in WEGS. - Proc. XXXVII, Part B2, Commission II (Edited by: Chen J, Jiang J, Kainz W) ISPRS Congress, 3-11 July 2008, Beijing, China, ISSN 1682-1750

Laudien R, Brocks S, Weyler S, Bareth G (2008b) Development and implementation of a multi-temporal SDSS scenario viewer by using ArcGIS Engine: The ArcGISDoubleMap- Panel, pp. 16-19. ArcUserVol. 11

Laudien R (2008c) Entwicklung und Programmierung räumlicher Entscheidungsunterstützungssysteme mit Java und ArcGIS Engine. 4th GIS Conference & ISPRS Workshop on Geoinformation and Decision Support Systems. http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/publikationsliste/1190_laudien_AGIT.pdf. Accessed 23 August 2009

Lautenbach S, Berlekamp J, Graf N, Seppelt R, Matthies M (2009) Scenario analysis and management options for sustainable river basin management: Application of the Elbe DSS. Environ Modell Softw 24:26-43

Ma J (1995) An object-oriented framework for model management. Decis Support Syst 13:133-139

Manoli E, Arampatzis G, Pissias E, Xenos D, Assimacopoulos D (2001) Water demand and supply analysis using a spatial decision support system. Global NEST: The International Journal 3:199-209

Matthews KB, Sibbald AR, Craw S (1999) Implementation of a spatial decision support system for rural land use planning: integrating geographic information system and environmental models with search and optimisation algorithms. Comput Electron Agr 23:9-26

Matthies M, Giupponi C, Ostendorf B (2007) Environmental decision support systems: Current issues, methods and tools. Environ Modell Softw 22:123-127

Morley M (2004) Decision-Support System Workbench for Sustainable Water Management Problems, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, Volume 1. http://www.iemss.org/iemss2004. Accessed 23 August 2009

NASA (2009) MODIS Rapid Response System. http://modis.gsfc.nasa.gov/. Accessed 23 August 2009

Ochola W, Kerkides P (2004) An integrated indicator-based spatial decision support system for land quality assessment in Kenya. Comput Electron Agr 45:3-26

Oosterbaan R (1998) SahysMod, mathematical salinity and groundwater model. http://www.waterlog.info/sahysmod.htm. Accessed 23 August 2009

Rango A, Martinec J (2000) SRM Snowmelt Runoff Model, http://ars.usda.gov/services/software/download.htm?softwareid=7. Accessed 23 August 2009

Riehle D (2000) Framework Design: A Role Modeling Approach. [ETH Zurich|Swiss Federal Institute of Technology]. http://dirkriehle.com/computer-science/research/dissertation/. Accessed 23 August 2009

Rizzoli AE, Young WJ (1997) Delivering environmental decision support systems: software tools and techniques. Environ Modell Softw 12:237-249

Schulz O, de Jong C (2004) Snowmelt and sublimation: field experiments and modelling in the High Atlas Mountains of Morocco. Hydrol Earth Syst Sc 8:1076-1089

Schulz O (2006) Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M'Goun, Zentraler Hoher Atlas (Marokko). Doctoral thesis, University of Bonn, Bonn. http://hss.uni-bonn.de/diss-online/math-nat-fak/2007/schulz_oliver/index.htm. Accessed 21 October 2009

Seffino LA, Medeiros CB, Rocha JV, Yi B (1999) WOODSS - a spatial decision support system based on workflows. Decis Support Syst 27:105-123

Segrera S (2003) Evolution of Decision Support System Architectures:applications for land planning and management in Cuba. J Comput Sci Technol 3:40-46

Shim JP, Warkentin M, Courtney JF, Power DJ, Sharda R, Carlsson C (2002) Past, present, and future of decision support technology. Decis Support Syst 33:111-126

Smith M (1992) CROPWAT: A computer program for irrigation planning and management. FAO, Irrigation and drainage paper 46. FAO, Rome

Sprague RH (1980) A framework for the development of decision support systems. MIS Quart 4:1-26

Toussi F (2008) HSQLDB Documentation. http://hsqldb.org/web/hsqlDocsFrame.html. Accessed 23 August 2009

Tsara M, Kosmas C, Yassoglou N (2005) An evaluation of the pesera soil erosion model and its application to a case study in Zakynthos, Greece. Soil Use Manage 21:377-385

Turban E, Aronson JE, Liang T (2004) Decision Support Systems and Intelligent Systems. Prentice Hall, Upper Saddle River, NJ

Uran O, Janssen R (2003) Why are spatial decision support systems not used? Some experiences from the Netherlands. Comput Environ Urban 27:511-526

Vacik H, Lexer MJ (2001) Application of a spatial decision support system in managing the protection forests of Vienna for sustained yield of water resources. Forest Ecol Manag 143:65-76

Verbourg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SS (2002) Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. Environ Manage 30:391-405

Williams JR, Dyke PT, Jones A (1983) EPIC-a model for assessing the effects of erosion on soil productivity. J Soil Water Conserv 38:553-573





3 Scenarios

3.1 Methodology of the IMPETUS-scenarios

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3.1.2 Definition of alternative scenarios and sub-regions within IMPETUS

3.1.3 Intervention scenarios

3.2 Climate scenarios

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3.2.2 The hierarchy of dynamical models

3.2.3 Construction of alternative climate scenarios

3.2.4 Characteristic tables and storylines for Benin and Morocco

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3.2.6 The statistical downscaling approach used in the High Atlas region

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3.4 Population projections for Benin

II-3 Scenarios

M. Christoph, B. Reichert, and A. Jaeger

In order to investigate the effects of Global and Regional Change on water resources and related issues, it is mandatory to develop a targeted, sound, and foresighted environmental assessment at appropriate geographic scales. This assessment must integrate social, technological, environmental, economic, and demographic issues. Scenarios that include expected developments in agriculture, economy, demography, and environment have become a state-of-the-art tool in environmental assessment and management (e.g., Gaiser et al. 2003; Millennium Ecosystem Assessment of UNEP (UNEP 2005); Alcamo 2008). Scenarios are consistent and plausible images of alternative futures that are comprehensive enough to support decision-making. Scenarios are not predictions or forecasts, but alternative development routes of complex systems. They enhance the information basis for decision-making through identifying the following: (1) the most important driving forces at the national and regional level; (2) sub-regional developments or events that are of national relevance; (3) the most important inter-linkages between national and regional development; and (4) the most important knowledge gaps and unanswered questions, which point to further actions needed. A meaningful scenario analysis must estimate a certain range of plausible developments that will enable decision-makers in public policy or private entities to deduce suitable advice from the results.

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II-3.1 Methodology of the IMPETUS-scenarios

M. Christoph, B. Reichert, and A. Jaeger

II-3.1.1 General definition of scenarios

Scenarios are usually a combination of qualitative and quantitative analyses that arise from the given differences between the scientific disciplines involved. While the natural sciences have a set of already existing numerical models to quantify driving forces, the social sciences, for example, give an interpretation of place-based analyses of human motivations. The use of models provides greater precision, rigor, and consistency with explicit assumptions and conclusions, but in the qualitative part, representing those processes for which little or even no numerical data are available, human motivations, values, and behavior can be incorporated. Therefore, scenario analyses must integrate disciplines across disciplinary frontiers. Scenario developments commonly consist of the following steps:

1. Generation of qualitative storylines describing the general societal, economic, and ecological characteristics and their main driving forces, but also the degree of their mutual interaction. The special and temporal scales for which the scenarios are valid must be defined. Ideally, a range of alternative scenarios, so-called ‘base scenarios,’ are developed. Stakeholder participation is a prerequisite in all, but especially in this first phase, because it is necessary to pinpoint the most pressing issues in the targeted area.

2. Quantification of the driving forces and simulation of the impacts, quantified by response indicators.

3. Generation of ‘intervention scenarios.’ These take the scenarios developed in steps 1 und 2 as base or reference scenarios. They are then used to analyze the influence of certain external events (e.g., war, economic crisis), policies, programs or single measures of the system under investigation.

Scenario analysis depends heavily on the selection of appropriate driving forces. A driving force (or a driver), in the definition of Carpenter et al. (2005), is "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem." Furthermore, Carpenter et al. (2005) distinguish between direct drivers and indirect drivers. While direct drivers, like Climate Change, definitely influence ecosystem processes, indirect drivers of change, such as demography, economy, technology, and culture, operate more diffusely.

II-3.1.2 Definition of alternative scenarios and sub-regions within IMPETUS

The IMPETUS scenarios are based upon different assumptions about the way in which water resources in the catchments will develop in the future. In order to provide a broad range of potential future developments with respect to water resources and related issues, two so-called 'reference scenarios' were developed that reflect more extreme, yet realistic, development paths. In a third reference scenario, the current trends persist. Following Carpenter et al. (2005), Climate Change is treated as an external direct driving force (see sect. II-3.2). It is, therefore, not explicitly included in the societal, economic, and ecological scenarios (see sect. II-3.3). Instead, a combination of both climate scenarios and socio-economic scenarios brackets the broad range of plausible futures.

Often, strong spatial inhomogeneities in demographic, economic, and natural framework conditions found in a specific target region require wisdom in dividing them into sub-regions, for which individual scenarios are then developed. If possible, this division should not cut across administrative boundaries.

Within the framework of IMPETUS, the research area in Benin, which covers most of the catchment area of the Ouémé river, has been divided into the following three scenario sub-regions (see fig. II-3.1.1a):

Higher Ouémé: This sub-region can be characterized as a rural region with a low population density and only one rainy season.

Middle Ouémé: This sub-region is also a rural region, and it forms the southern border of transhumance.

Lower Ouémé: This sub-region, in contrast, is characterized by a well-developed infrastructure and shows a high rate of urbanization that goes hand-in-hand with a high population density. There are two rainy seasons.

The research area in Morocco, from the upper Drâa valley to Lake Iriki, was divided into the following three scenario regions (see fig. II-3.1.1b):

High Atlas: This sub-region can be characterized as a marginalized mountain region with a poorly developed infrastructure. Water availability is, however, relatively good, and is thus only a weak limiting factor for agricultural production.

Basin of Ouarzazate: Good water availability is a specific feature of this sub-region. It is also characterized by a well-developed infrastructure and strong urban centers in Ouarzazate, Boumalne Dadès, Kalaat M'gouna, Taznakht and Tinghir.

Oases south of the Mansour Eddahbi Dam: Low water availability is a main impediment for economic development is this sub-region. Agriculture is dependent on the management of the Mansour Eddahbi Dam.

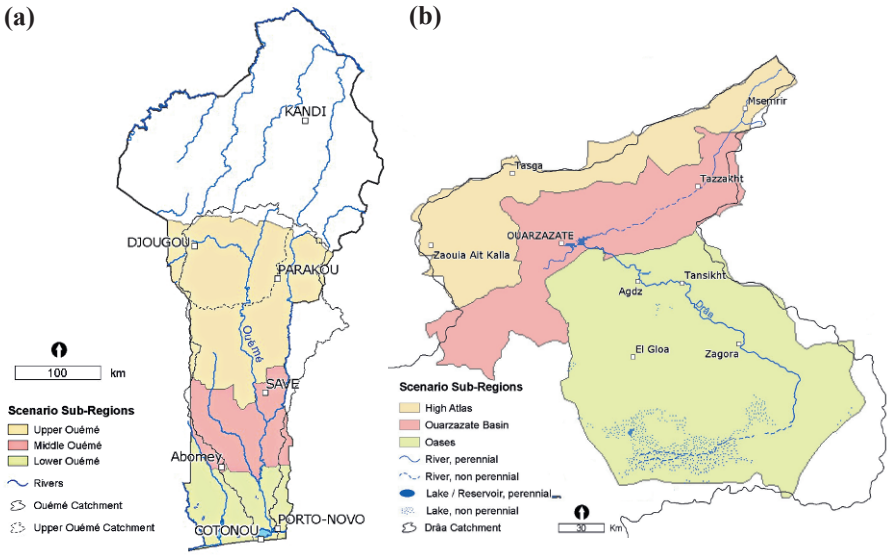

Fig. II-3.1.1: Scenario regions: a) Benin b) Morocco.

II-3.1.3 Intervention scenarios

Intervention scenarios allow the decision maker to depict future consequences of policy interventions. In other words, they describe the future state of society and the environment under the influence of a certain policy or decision. Intervention scenarios are also known as 'mitigation' or 'policy' scenarios. In the schematic below (see fig. II-3.1.2), the principles of intervention scenarios are given: the red curves depict the temporal evolution of the three reference scenarios (including a business-as-usual scenario) for a certain quantity of interest, i.e., a response indicator. An action X at time t_1 or an action Y at time t_2 will significantly change the temporal evolution path (blue lines) of the response indicator until the target year 2025.

So far, no decision maker can foresee whether or not his or her intervention will have the desired quantitative effect on the target variable (e.g., the amount of ground water available in an aquifer). There are too many parameters (or response indicators) influencing the target variable, and their interdependencies are too complex to overlook. A computer-based decision support tool as designed in the IMPETUS project (see sect. II-2.1), however, offers the decision maker the option to “play god” as they are guided through the three reference scenarios offered with various options for interventions at different levels. The result of their decision(s) on the target variable will then be graphically depicted and will serve as a scientifically sound basis for the decision maker’s ‘optimal’ policy.

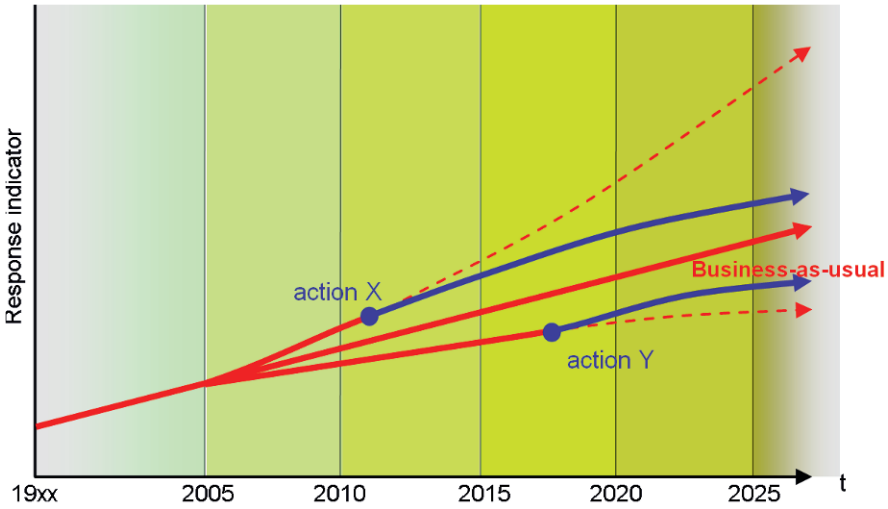

Fig. II-3.1.2: Schematic of intervention scenarios.

References

Alcamo J (ed) (2008) Environmental futures: The Practice of Environmental scenario Analysis. Elsevier, Amsterdam

Carpenter SR, Pingali PL, Bennett EM, Zurek MB (eds) (2005) Ecosystems and Human Well-being: Scenarios. The Millennium Ecosystem Assessment series 2. Island Press, Washington DC

Gaiser T, Krol M, Frischkorn H, Araújo JC (eds) (2003) Global change and regional impacts. Water availability and vulnerability of ecosystems and society in the semiarid northeast of Brasil. Springer Verlag, Berlin and Heidelberg

UNEP (2005) Millennium Ecosystem Assessment. http://www.millenniumassessment.org/. Accessed 12th November 2009

II-3.2 Climate scenarios

M. Christoph, A. H. Fink, H. Paeth, K. Born, M. Kerschgens, and K. Piecha

Abstract

The principal method of generating regional climate scenarios is explained. Based on a hierarchy of climate models and different downscaling techniques, an understanding of atmospheric processes, and historical climate data, three alternative scenarios are developed for the river catchments under investigation and their subregions. The outcomes of this process are qualitative and quantitative storylines for use by non-climate experts. Results from a dynamical and statistical regionalization approach using the REMO model are discussed for Benin. For Morocco, the alternative statistico-dynamical approach is outlined. In the final section, the methods are critically reviewed in terms of their suitability for climate impact studies.

Keywords: Storylines, regional climate model, Climate Change, trends, process understanding, land use, temperature, precipitation, dynamical downscaling, SRES scenarios, statistico-dynamical downscaling, statistical downscaling, Weather Generator

II-3.2.1 Introduction

The AR4 (Fourth Assessment Report) of the IPCC (Intergovernmental Panel on Climate Change, IPCC 2007), which is based on an ensemble of global general circulation models (GCMs), projects an overall warming trend for Africa and a substantial drying for sub-tropical North Africa for different emission scenarios until the end of the 21st century. The rainfall projection for tropical West Africa for this century is uncertain. Global climate models used in the IPCC 4AR, for example, differ considerably in the rainfall trend for West Africa using the A1B emission scenario (Christensen et al. 2007, supplementary figure S.11.13). In order to pursue detailed climate impact analyses from other disciplines (e.g., hydrology, agronomy, health), it is important to recognize that this information is highly insufficient due to its coarse resolution in both space and time. Furthermore, the credibility of these projections has to be questioned due to the physical parameterization of sub-grid processes and the omission of relevant anthropogenic forcing factors (e.g., loss of vegetation and degradation of soils).

Thus, high-resolution regional climate scenarios or, more precisely, 'regional Climate Change projections' are indispensable for impact studies. According to

AR4, these should ideally be based upon information from four potential sources: (1) global climate model simulations; (2) downscaling of simulated data from these global models using techniques to enhance regional details; (3) physical understanding of the processes governing regional responses; and (4) recent historical Climate Change (Christensen et al. 2007). All suggested pathways have been pursued within IMPETUS for the Drâa and the Ouémé catchments and its sub-divisions (see sect. II-3.1). As described below, this approach has resulted in a set of regional climate scenarios spanning the so-called phase space of likely and plausible future climatic changes.

II-3.2.2 The hierarchy of dynamical models

In the IMPETUS project, a combination of state-of-the-art dynamical and statistical-dynamical approaches have been applied to meet the above-mentioned IPCC suggestions (1) and (2) with respect to the development of regional climate scenarios. The backbone of the dynamical downscaling technique constitutes a hierarchy of nested dynamical models of the atmosphere as displayed in figure II-3.2.1. On top of this model chain, one can find the global-scale GCM (general circulation model) ECHAM5 (European Centre Hamburg Model Version 5, Roeckner et al. 2003) coupled with the MPI-OM (Max-Planck-Institute dynamical Ocean Model). This ocean-atmosphere coupled model has a horizontal resolution of about 200 km, and it allows for multi-century integrations. It is forced with increasing

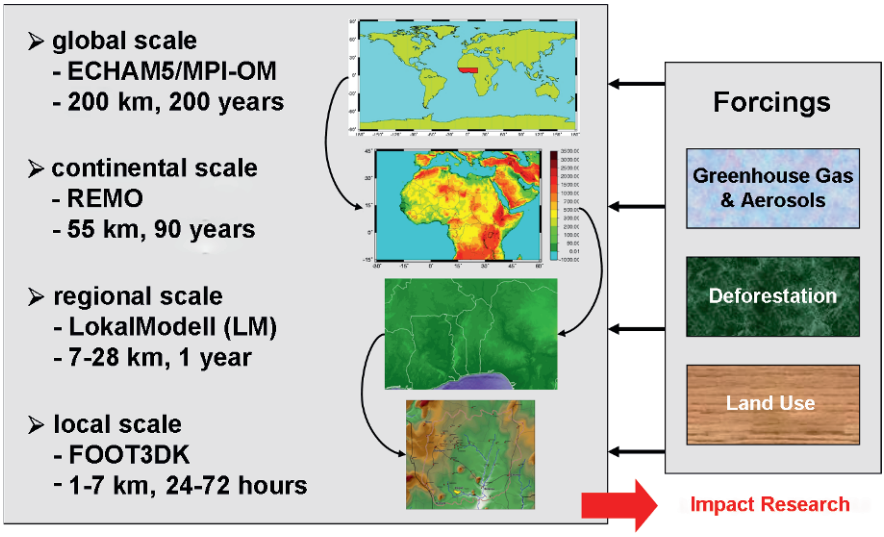

Fig. II-3.2.1: The IMPETUS model hierarchy and driving forces.

greenhouse gas concentrations and sulphate aerosols: as observed historically and according to the IPCC SRES (Special Report on Emission Scenarios) A1B and B1 for the present day until the year 2100. Land use changes are not taken into account. The REMO (Regional Model) regional climate model (Jacob 2001) addresses the synoptic processes at the continental scale: the model has a horizontal resolution of 0.5° (an approximately 55-km grid box spacing) and covers tropical and northern Africa. It has been nested into the GCM, and multi-decadal simulations have been carried out up to the year 2050. Future losses in vegetation and the degradation of soils were considered according to FAO (Food and Agriculture Organization) estimations (Paeth et al. 2009). On the regional scale, the non-hydrostatic LM (Lokalmodell) of the DWD (German Weather Service) has been nested into REMO. The horizontal resolution is between 28 – 7 km and the integration time is up to one year. At the lower end of the model hierarchy on the very local scale, the non-hydrostatic model FOOT3DK (Flow Over Orographically Structured Terrain, 3-dimensional, Köln Version) is used with a horizontal resolution between 7 – 1 km and with a total simulation time on the order of one to three days. For technical aspects of the downscaling techniques and the results obtained, the reader is referred to sections II-3.2.5 and II-3.2.6.

II-3.2.3 Construction of alternative climate scenarios

It is important to note that research within IMPETUS has revealed that not all regional climate processes are adequately represented in the numerical models. In order to cover the range of plausible pathways of regional Climate Change, three regional climate scenarios are defined based on:

a) Climate model projections

b) Process understanding

c) Persistence of recently observed trends (business as usual)

To construct the (a)-scenario, an ensemble of regional model simulations – driven by global IPCC greenhouse gas emission scenarios A1B and B1 (see box below) and FAO-based land use changes – were performed using the IMPETUS model hierarchy (see fig. II-3.2.1) and statistical downscaling techniques. This has resulted in a set of high-resolution (both in space and in time) time series of relevant climate parameters. It has also enabled the simulation of a wide range of impacts involving the application of numerical and expert models of other disciplines such as agriculture, hydrology and health (see, e.g., sect. II-4.1, II-4.2, II-4.5, and II-5.1). Note that the SRES scenarios A1B and B1 are an external forcing of the GCMs (and, thus, an indirect forcing of the regional models used) and must not be mixed up with the (a)-scenarios generated within the framework of the IMPETUS project. It should be mentioned here that most impact studies described in part II of this book use (a)-scenario time series that were generated from REMO output in

which REMO was nested in the ECHAM-GCM and forced with either A1B or B1 global emission scenarios. When REMO scenarios with a 0.5° resolution were still too coarse, or point information was needed, further downscaling was carried out by using a Weather Generator. For clearer signal differences between A1B and B1, forced REMO output for the target year for some impact studies was extended to 2050. Note that mathematical models could not be applied in the (b)- and (c)-scenarios, and thus the impact studies were rather limited. Nevertheless the (b)- and (c)-scenarios are very important for judging the quality of the (a)-scenarios.

Box: Storylines taken from the IPCC Special Report on Emissions Scenarios: Summary for Policymakers (IPCC 2007).

A1: The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

B1: The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

II-3.2.4 Characteristic tables and storylines for Benin and Morocco

As mentioned in the foreword (see sect. II-3.1), the IMPETUS catchments are divided into three sub-regions. As a consequence, the *climate model projections* are given for each sub-region separately. The target years are 2025 and 2020 for Benin and Morocco, respectively (see also subsect. II-3.3.1). In the following tables, characteristic Climate Changes for each catchment with its sub-regions are given

for the three alternative climate scenarios. These tables are followed by both qualitative and quantitative storylines. A storyline is, by definition, a narrative description of a scenario that highlights the main scenario characteristics and dynamics and the relationships between key driving forces. This is done to help none-climate experts and decision makers get a concise overview of the quintessence of different climate scenarios.

Table II-3.2.1: Characteristics of the climate scenarios for Benin.

Scenario (a)	Scenario (b)	Scenario (c)
	Upper Ouémé	
- strong reduction in annual rainfall - less heavy rain events - delayed monsoon onset - remarkable warming (particularly in summer)	- strong reduction in annual rainfall due to stronger wind convergence at the coast and land degradation - substantial warming - stronger climate extremes	- land degradation and warmer surface temperatures in the Indian Ocean, maintaining below-normal precipitation anomalies - warming of 0.35°C per decade
	Middle Ouémé	
- slight weakening of the hydrological cycle - slightly enhanced seasonality - strong warming	- moderate weakening of the hydrological cycle due to less evapotranspiration upstream (enhanced land use) - considerable warming - stronger climate extremes	- land degradation and warmer surface temperatures in the Indian Ocean, maintaining below-normal precipitation anomalies - warming of 0.15°C per decade
	Lower Ouémé	
- strong reduction in annual rainfall and delayed onset - less heavy rain events - reduced climate seasonality and earlier withdrawal - strong warming	- enhanced precipitation due to an intensified summer monsoon circulation and latent heat fluxes over the Gulf of Guinea - moderate warming	- land degradation and warmer surface temperatures in the Indian Ocean, maintaining below-normal precipitation anomalies - no temperature trend

Storyline for scenario (a) in Benin: *Climate model projection*s

Results for target year 2025 show a reduction in average annual precipitation over Benin. There is, however, a regional difference, with clearly reduced precipitation, in the coastal areas and in the Upper Ouémé valley, whereas in Central Benin, slightly more humid conditions are expected. The trend toward a drier climate is especially manifested in a reduction of intense rainfall events. In general, the seasonality of rainfalls will weaken in the south and north of Benin but strengthen in the Middle Ouémé valley. The onset of the rainy season is likely to be delayed in all parts of the country. At the coast the monsoon will begin up to

12 days later. Furthermore, Benin will be characterized by a significant warming trend throughout the next two decades, reaching more than 2°C within just 20 years, especially in the summer. The weakening of the hydrological cycle appears most notably in the local recycling of precipitation. This also implies a clear reduction in evaporation in most parts of the country. However, no significant changes in the monsoon circulation are expected.

Uncertainties in modeled Climate Changes arise from the influence of mineral dust and aerosols from biomass burning, which is not taken into account, and from a poor representation of the most important rain-producing weather systems in West Africa, which are the organized MCS (meso-scale convective systems).

Storyline for scenario (b) in Benin: *Process understanding*

Our knowledge of the effects of global warming on the climate of tropical Africa has been broadened within the framework of IMPETUS. Increasing greenhouse gas concentrations warm the tropical oceans and thus induce far-reaching anomalies in atmospheric circulation, in the spatial distribution of high-reaching cloud covers, and in convective precipitation events. Process understanding suggests an increase in the meridional precipitation gradient over sub-Saharan West Africa. This is due to the fact that the warming of the tropical Atlantic, especially of the Gulf of Guinea, is, in general, associated with an enhancement of the convective activity in the coastal areas of West Africa and with drier conditions farther inland, such as in the Sudanian and Sahel regions. In the coastal areas up to 200 km inland, the water vapor source for precipitation is the nearby ocean. The resulting direct influence of the higher sea surface temperatures is enhanced by the rain-producing land-sea breeze circulation. For Benin, such a development means higher amounts of precipitation in the southern parts of the country until 2025 and drier conditions in the Upper Ouémé valley. The latter is explained by the fact that the precipitating water vapor in the Upper Ouémé valley partly has its origin from the evapotranspiration over the regions upstream of the southwesterlies. It is assumed that the so-called “water vapor recycling” will be further reduced due to land use changes in the humid Guinea coastal areas. Furthermore, it is expected that higher water vapor contents will increase the intensity of extreme rainfall events. Increasing greenhouse gas concentrations in the atmosphere and the warming of the oceans will also lead to warmer surface temperatures over land. An additional warming over the northern parts of the country is to be expected from reduced precipitation and evaporation. As a consequence solar radiation is transformed to a higher degree into sensible heat. Higher temperatures during the dry and rainy seasons will enhance the seasonal drying of the soils and the water stress on plants during dry episodes in the course of the rainy season.

This process-understanding scenario does not take into account teleconnections (e.g., El Niño/Southern Oscillation) or complex non-linear interactions within the climate system.

Storyline for scenario (c) in Benin: ***Persistence of recently observed trends (business as usual)***

For several decades, the entire sub-Saharan West Africa has encountered an increasing number of clearly below-normal amounts of annual rainfall. For Benin, we also observe a trend toward reduced precipitation amounts since the late 1960s. Since the mid-1990s the water temperatures in the tropical Atlantic have changed in a way that would favor higher precipitation throughout the entire tropical West Africa. However, rainfall amounts remain below the level they reached during the wet period in the middle of the 20th century, despite the fact that in recent years a tendency toward higher rainfall sums has been observed (Ali and Lebel 2009). The wet period then was associated with a very similar distribution of sea surface temperatures found in recent years. Model studies suggest that the return to wetter conditions fails due to the degradation of vegetation and the con-

Table II-3.2.2: Characteristics of the climate scenarios for Morocco.

Scenario (a)	Scenario (b)	Scenario (c)
	High Atlas	
- snow line rise by 200 m - reduced precipitation due to decreasing number of lows from the north - reduced seasonality - strong warming in winter	- snow line rise by 200 m - more intense but less frequent precipitation events - not trend in annual precipitation - more extreme precipitation events	- snow line rise by 200 m - ongoing tendency towards reduced precipitation in winter - still large interannual variability
	Basin of Ouarzazate	
- substantially reduced precipitation and seasonality - more intense but less frequent precipitation events from tropical-extratropical interaction - strong warming in winter	- slightly increased precipitation amounts due to enhanced moisture transport for: a) tropical-extratropical interaction b) pressure minima off the Moroccan coast	- no change in the longterm mean precipitation amount - still tendency toward dry or wet periods of several years (decadal variability)
	Southern oasis	
- slightly reduced precipitation - more intense but less frequent precipitation events from tropical-extratropical interaction - reduced seasonality - weak warming in winter	- slightly increased precipitation amounts due to enhanced moisture transport for: a) tropical-extratropical interaction b) pressure minima off the Moroccan coast	- no change in the longterm mean precipitation amount - still tendency toward dry or wet periods of several years (decadal variability)

tinuous warming of the Indian Ocean. In this present scenario, we assume that these two rainfall-inhibiting factors continue to exist. Hence, we project the persistence of below-normal precipitation in all parts of Benin until 2025.

In addition, a progressive warming of the land surface has been measured in the past. Under the assumption of a continuous rise in global greenhouse gas concentrations and an increasingly uncontrolled change in land use by a steadily growing population, the warming trend will persist at a rate of 0.2°C per decade.

Storyline for scenario (a) in Morocco: *Displacement of the NAO*

Numerous climate models project a displacement of the poles of the NAO (North Atlantic Oscillation; defined as a normalized pressure difference between Iceland and the Azores) toward the northeast, leading to enhanced storm activity over northern Europe and drier conditions in the Mediterranean. This effect on the region under investigation can be studied with the help of the IMPETUS atmospheric model chain. Due to the northward displacement of the mean position of the polar front, the cyclone tracks are also shifted to the north. As a consequence, synoptic disturbances in the mid-latitudes reach the Atlas Mountains less frequently, thereby clearly reducing the winter precipitation in the High Atlas. This signal also extends to the regions south of the Atlas Mountains. The results of the dynamical regionalization based on the REMO model show a precipitation reduction in the High Atlas of -38%. Diagnostic studies were carried out during the first phase of IMPETUS to investigate the underlying mechanisms of precipitation generation in the southern parts of the catchment. Particularly the identified tropical-extratropical interaction mechanism that is responsible for the advection of humidity from the tropics to the southern slopes of the Atlas Mountains has not been represented adequately because of the coarse resolution of the global climate models. The REMO model results also show a reduction in precipitation in the Ouarzazate Basin (-43%) and in the southern oases (-33%) due to boundary forcing by the ECHAM5 global climate model. In individual cases, however, the observed tropical-extratropical interaction is represented correctly by the LM model (*Lokalmodell* of the German Weather Service), which simulates more intense precipitation events due to enhanced humidity advection. The warming of the atmosphere and the resulting enhancement of humidity transports can only partially compensate for the projected negative precipitation trend. We assume a tendency toward less frequent but more intense precipitation events by tropical-extratropical interactions throughout the transitional seasons. In summary, the mean annual precipitation is reduced substantially in the High Atlas and only moderately in the Ouarzazate Basin and in the southern oases.

Storyline for scenario (b) in Morocco: *Enhancement of the humidity advection*

All processes leading to precipitation in the area south of the Atlas Mountains have been thoroughly investigated within the IMPETUS framework. Precipitation in the High Atlas is generated mainly by the low-pressure activity of the mid-latitudes during the cold months. Precipitation systems reaching the ridges of the High Atlas from the north can also bring precipitation to the southern slopes. These systems are mainly responsible for the available water in the Drâa region, especially when snowflakes are blown across the Atlas divide or snow drift transport occurs from its northern to its southern side during the cold season. In the Ouarzazate Basin and in the southern oases, this mechanism has no influence on precipitation. In the latter regions, precipitation is generated mainly by troughs or cut-off lows located west of the Moroccan coast. These systems draw their humidity either from local evaporation over the ocean or by tropical-extratropical interactions from areas south of the Sahara. In the latter mechanism, moisture from convective clusters or squall lines over tropical Africa and the adjacent Atlantic Ocean, which is transported northward on the eastern side of a subtropical upper-level trough located to the west of northwestern Africa, is a decisive factor. The advection of moist air from the south toward the slopes of the Atlas Mountains leads to forced lifting, which results in the condensation of water vapor and, eventually, the formation of precipitation.

Due to atmospheric warming as a result of increased greenhouse gas concentrations, the air can take up and transport more humidity. In this scenario, it is assumed that the dynamic processes of precipitation generation in the Drâa valley remain unchanged. The enhanced humidity advection due to the temperature rise leads to increased amounts of precipitation. The statistical-dynamical regionalization of global climate model simulations with the help of the IMPETUS atmospheric model chain shows that for the southern oases, a slight increase in cut-off lows west of the Moroccan coast can be expected. Although these events are quite rare, they are responsible for most of the precipitation in the Ouarzazate Basin and in the southern oases. Even a slight increase in such events leads to a noticeable rise in precipitation amounts. In addition, the rise in air temperature is responsible for increased horizontal water vapor transports per event.

Storyline for scenario (c) in Morocco: *Trend extrapolation*

The area south of the Atlas Mountains is characterized by an extreme interannual variability in precipitation. In the Ouarzazate Basin and southern oases in particular, mean precipitation values result from averages over many very dry years and some relatively humid years. Superimposed is a prominent decadal variability that can lead to a misinterpretation of trends when considering time intervals that are too short. In the two southern sub-regions of the catchment, then, no clear trend can be diagnosed with respect to mean precipitation amounts. A reliable trend to-

ward reduced snowfall in winter is observed solely in the High Atlas, despite the presence of high interannual variability. In this scenario we assume that the observed trend toward winters with lower precipitation, together with a pronounced interannual variability, continues in the High Atlas. In contrast, the Ouarzazate Basin and the southern oases are better characterized by a large decadal variability. If this tendency persists, the southern parts of the catchment will receive constant amounts of annual precipitation, but they will experience pronounced decadal variability. The occurrence of several consecutive dry or wet years will continue.

II-3.2.5 Dynamical downscaling, model bias correction, and the Weather Generator (WEGE): An example for Benin

For the simulations with REMO, land cover changes are converted into model grid box parameters, like vegetation and forest fraction, albedo, leaf-area index and roughness length at the model's scale (Paeth et al. 2009). The combined GHG (greenhouse gas) and LUCC (land use and land cover change) scenario is supposed to be more realistic than the classical IPCC scenario approach with radiative forcing alone (IPCC 2007). This is because the effect of land degradation is evident from observational data and can be assumed for the future as well (Zeng et al. 2002; Feddema et al. 2005).

The process of increasing land use and deforestation in Africa is difficult to anticipate because it takes place at the local scale and is subject to random processes in space and time. Nonetheless, the large-scale process of land degradation is mainly dependent on demographic growth, which can be projected with quite high confidence. Based on FAO and UN (United Nations) estimates on regional population growth in Africa, a stochastic model has been developed that produces a random pattern of high-resolution land use changes at the 1 km by 1 km scale of the USGS land cover classification data set (Hagemann 2002). In addition, some reasonable constraints have been taken into account. These include, for instance, accelerated land degradation along traffic axes, around urbanized areas and in the desertification belt in the Sahel Zone. The result is a transient pattern of land use changes (LUCC) that reflects the spatial heterogeneity of the real process and is consistent with the FAO and UN estimates at the regional-mean level. Between 2000 and 2025 the expected demographic growth leads to a general transformation from forests and woody savannas to croplands and savannas in West Africa. In addition, the urbanization proceeds, especially along the Guinea Coast. For details of the LUCC assessment until 2050, the reader is referred to Paeth et al. (2009).

Post-processing of climate model data

All climate models are subject to systematic errors. These arise from limited resolution, uncertain physical parameterizations, neglected feedbacks, and unknown processes (Xu 1999). Precipitation, especially, is the end product of a causal chain of nonlinear processes like radiation, convection, and cloud microphysics. These are usually parameterized and, hence, characterized by nonlinear error growth. While systematic errors may be less troublesome for the analysis of climate trends, they are strictly problematic when climate model data are used as quantitative inputs for impact studies. This is particularly true for hydrological applications (Lebel et al. 2000). Hydrological models mostly require rainfall information at a very high spatio-temporal resolution. In the IMPETUS project, this information is taken from simulations with the REMO regional climate model (Jacob 2001). While REMO is able to reproduce most of the basic features of the observed African climate (Paeth et al. 2005), simulated precipitation is systematically underestimated over sub-Sahelian West Africa (see fig. II-3.2.2). In addition, the 0.5° resolution of REMO is inconsistent with the local rainfall information required by hydrological and other impact models used in IMPETUS.

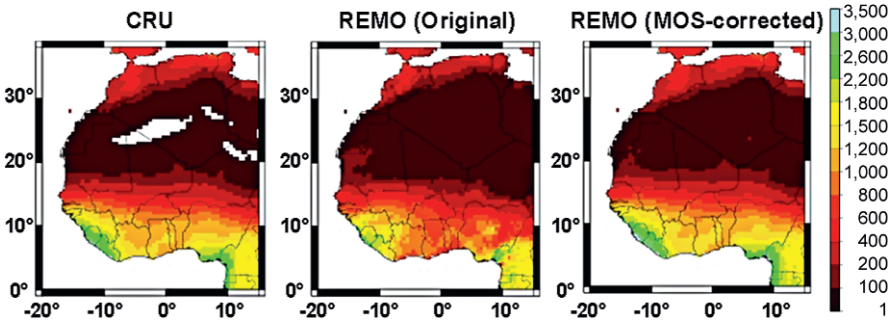

Fig. II-3.2.2: Long-term mean pattern of observed annual precipitation in West Africa from observations (CRU, New et al. 2000), original REMO output and REMO output corrected by MOS.

Because of these limitations, a two-step post-processing of the simulated precipitation data from REMO has been undertaken prior to using the data for impact studies in IMPETUS:

(1) The systematic errors in the monthly rainfall totals and the seasonal cycle have been adjusted to observed values from the CRU (Climate Research Unit) data set (New et al. 2000) by carrying out MOS (Model Output Statistics; Hansen and Emanuel 2003). In the present case, the MOS consists of a multiple linear regression model with a stepwise extension of predictors and a cross validation approach, which are used to identify robust predictors (Paeth 2010). In addition to simulated precipitation, the predictors are simulated sea-level pressure, wind, geo-

potential height, and temperature. These kinematic and thermodynamic variables are assumed to be linked to observed precipitation and to be more reliable from climate models than from simulated rainfall. The MOS-corrected precipitation climatology is presented in figure II-3.2.2. In the figure, it is evident that the corrected model precipitation is now in good agreement with the observed pattern.

(2) The MOS correction still leads to regional-mean precipitation on the basis of the 0.5° by 0.5° model grid boxes. At the daily scale, this regional-mean presentation differs strongly from the real spatial distribution of the rain events. This is particularly true in tropical Africa, where mesoscale convective systems and squall lines are associated with a very heterogeneous pattern of locally confined rain events (Fink and Reiner 2003; Fink et al. 2006). In order to transform the MOS-corrected regional-mean precipitation from REMO to a local pattern of rain events, a WEGE (Weather Generator) has been developed in the IMPETUS project. This Weather Generator is centered over Benin according to the focus of the hydrological models. The WEGE produces virtual station data, matching the BDMET (*base de données météorologiques*) stations in Benin (Le Barbé et al. 2002), and is composed of three components (see fig. II-3.2.3): (i) The dynamical part is taken from the MOS-corrected REMO precipitation. This part represents the synoptic-scale atmospheric processes and the Climate Change signals. (ii) The relationship between topography, atmospheric flow, and windward-lee effects on local rainfall is used as a physical downscaling component. (iii) A large part of the spatial distribution of rain events is random. This stochastic component is derived from observed station data in Benin and is found to account for more than 90% of the subgrid-scale rainfall distribution. The resulting 'virtual' station data set is finally adjusted to the statistical characteristics of the observed daily precipita-

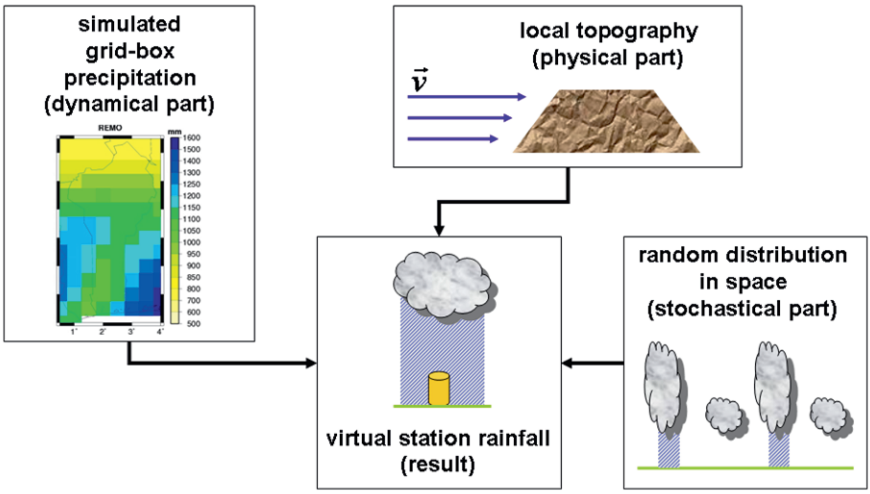

Fig. II-3.2.3: Scheme of the Weather Generator with dynamical, physical and stochastic components leading to virtual station data with local rainfall information.

tion at the BDMET stations by so-called probability matching (Helmer and Ruefenacht 2005). This is a procedure that transforms a data set with a simulated distribution function to a new data set that matches the observed distribution function. The final data set maintains the larger-scale climate signals from REMO, and it agrees with the typical spatial and temporal distribution of the observed rain events in Benin.

Figure II-3.2.4 depicts the efficiency of the WEGE. Compared with the observations, the time series of simulated daily precipitation from the original REMO output reveals an incorrect seasonal cycle that underestimates heavy rain events and misses dry spells during the rainy season. The time series produced by the WEGE is in good agreement with the observations. Note that the WEGE is not meant to reproduce the observed sequence of daily rain events, but their statistics. This is demonstrated in figure II-3.2.5. Here, the Gamma distribution of the observed daily rainfall is inconsistent with the original model output, which tends to underestimate the extreme events while weak rainfall events occur too frequently. In contrast, daily precipitation from the WEGE corresponds to virtually the same Gamma distribution as the observations. The post-processed precipitation data from REMO proved to be sufficiently reliable for various impact studies in the IMPETUS project, including hydrological modeling and the crop and malaria models.

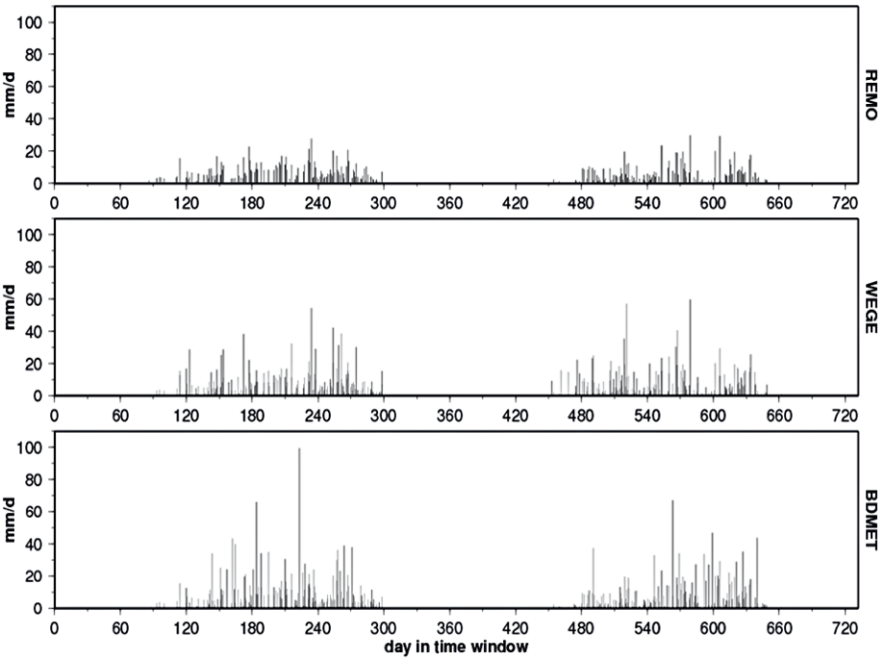

Fig. II-3.2.4: Time series of daily rain events at Abomey-Calavi station during two exemplary years from original REMO output, virtual station data from the Weather Generator (WEGE), and observations (BDMET, Le Barbé et al. 2002).

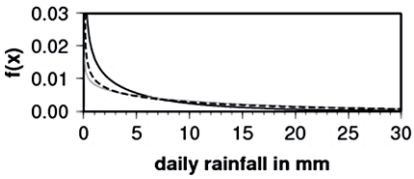

Fig. II-3.2.5: Gamma distributions of daily rain events at Abomey-Calavi station from original REMO output (black solid line), virtual station data from Weather Generator (grey solid line), and observations (black dashed line).

The simulated changes in annual-mean near-surface temperature according to the A1B scenario and the IMPETUS LUCC assessments until 2050 (see Paeth et al. 2009) are shown in figure II-3.2.6a. The highest amplitude with up to 4.5°C warming until 2050 occurs in sub-Sahelian Africa, exactly where the prescribed LUCC peaks. The greenhouse gas forcing without LUCC leads to a slightly different picture with more homogeneous warming rates over the land masses (not shown). From the comparison of the A1B scenario with and without LUCC it can be derived that the LUCC contributes around 1°C – equivalent to one third – to the overall heating. Of course, this effect is confined to sub-Sahelian Africa

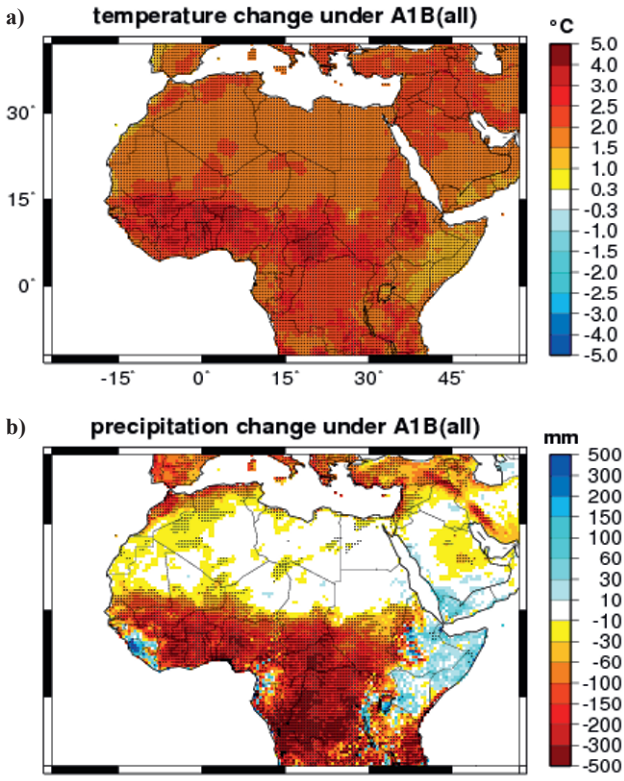

Fig. II-3.2.6: Simulated linear changes in ensemble-mean annual temperature in °C (a) and precipitation in mm (b) for the combined A1B and LUCC scenario (for details see text) based on three REMO ensemble realizations. Statistically significant trends at the 5% level are dotted.

where the LUC mainly takes place. In all regions and scenarios the temperature trends are statistically significant and are consistent with different ensemble members. The trend patterns of annual precipitation are much more heterogeneous in space (see fig. II-3.2.6b). The combined radiative and LUCC forcing lead to a remarkable drying on the order of 25 to 40% of the present-day totals. In contrast, the greenhouse gas forcing alone comes along with a completely different trend pattern with mostly incoherent and insignificant changes. This implies that the weakening of the hydrological cycle over sub-Saharan Africa is mainly linked to land degradation rather than radiative heating.

In summary, the consideration of the continental-scale changes in land use and land cover until 2050 in the regional model REMO caused a significant drying trend that is already discernible in about the middle of this century. Moreover, the significant greenhouse gas induced temperature trend pattern was changed in a reasonable manner when compared to the IPCC 4AR A1B scenarios; the strongest warming occurs in the savanna belt of West Africa rather than in the western Sahara. These novel findings were utilized in several Climate Change impact assessments for West Africa (e.g. sect. II-4.1, sect. II-4.2, and sect. II-4.5).

II-3.2.6 The statistical downscaling approach used in the High Atlas region

For hydrological applications, time series of daily meteorological parameters are particularly crucial. Therefore, a purely statistical downscaling of climate scenarios has also been undertaken for the Drâa region. The objective of the downscaling was to create time series of rainfall, temperature, moisture, radiation, and wind for the near-surface layer (2 m-height) with daily resolution from REMO climate model data. Statistical properties of climate model data usually differ considerably from point observations because model variables are always calculated as representative averages for modeled grid boxes. As a consequence, in the case of rainfall the model tends to predict more frequent, lower intensity rainfall than is observed.

Because of this discrepancy, it is clear that for the atmospheric forcing of hydrological models, results of regional climate models have to be transformed so that their statistical characteristics more closely correspond to the observational data. The most important parameters to be transformed are rainfall rates and temperatures. An additional issue for the practical application of climatic data is the reduction of the amount of data. For this purpose, the Drâa region was divided into a small number of zones either by similar climatic characteristics or as subcatchments of the Drâa and its tributary rivers.

Although relatively easy to determine, the most important predictors for small-scale variability are topographic characteristics like surface elevation and land use data. In the statistical downscaling approach used here, they have been aggregated on a 1-km grid. The procedure consists of two steps: the estimation of a transfer

matrix based on multiple regression methods and the correction of statistical properties of rainfall.

In the first step, regression coefficients of sufficient predictors with parameters taken from observing stations are calculated in a multiple regression. The observational data set used consists of four climatic stations located between Ouarzazate and the High Atlas Mountains (Ouarzazate, Agouim, Ifre, and Ait Mouted), and the IMPETUS climate stations (see sect. I-4.3). Predictors are climate model data and topographic characteristics. In the Drâa valley, surface elevation, exposure, and location in space are the most important candidates for topographic predictors because local climate conditions are steered by three factors: (i) the NW-SE gradient of rainfall, (ii) surface elevation, and (iii) slope of the surface (in the northern hemisphere, a northerly slope will be slightly cooler and wetter than a southerly slope). The resulting transfer matrix is applied on a combined set of predictors consisting of climate model data and the above-mentioned topographic data. For temperature, wind, and relative humidity, this first step is applied to daily data. Due to the high day-to-day variability for rainfall, the first step is applied only for annual and monthly data.

In the second step, statistical properties of rainfall data from observations are transferred to the climate model data. This is done by estimating the height-dependent seasonal march of rainfall probability from observations and recalculating the number of rainfall days in model data under the constraint of preservation

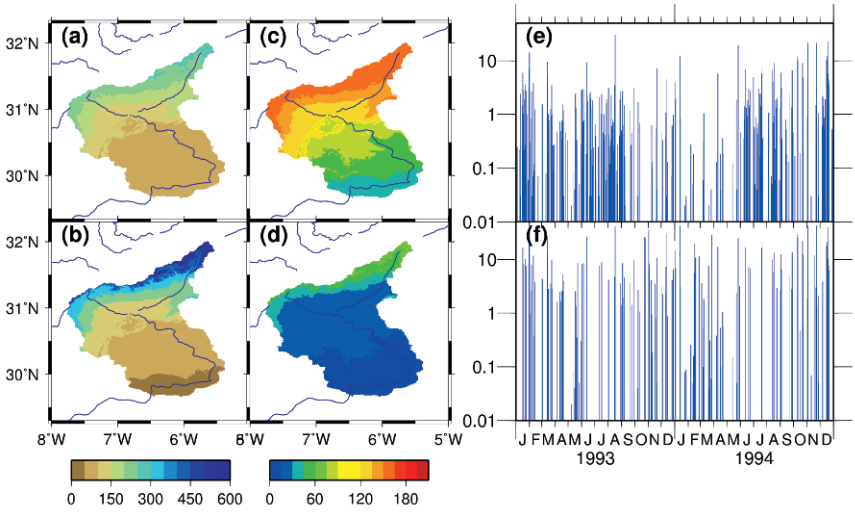

Fig. II-3.2.7: Results of statistical downscaling. The top row shows REMO rainfall 1960-2000 using multiple regression coefficients obtained from climate model data and topography: (a) mean annual rainfall sums in mm, (c) average number of rainy days per year, (e) exemplary time series of daily rainfall for the high mountain zone in mm/day. The bottom row, images (b), (d), and (f) shows the same for rainfall interpolated using regression coefficients from climate station observations.

of monthly rainfall sums. This results in less frequent but more intense rainfall, as presented in figure II-3.2.7.

The assessed changes in climate scenarios for the period 2011-2050 are shown in figure II-3.2.8. The maps reveal that the rainfall is reduced between 5% (mountainous areas) and 30% in the southern regions for the SRES A1B scenario and by 5% and 20% for the B1 scenario. Atmospheric warming is represented by the 2 m-temperature accounts for 1.2°C in the SRES A1B and 1°C in the B1 scenario; for both scenarios, it is slightly more pronounced in the mountain region.

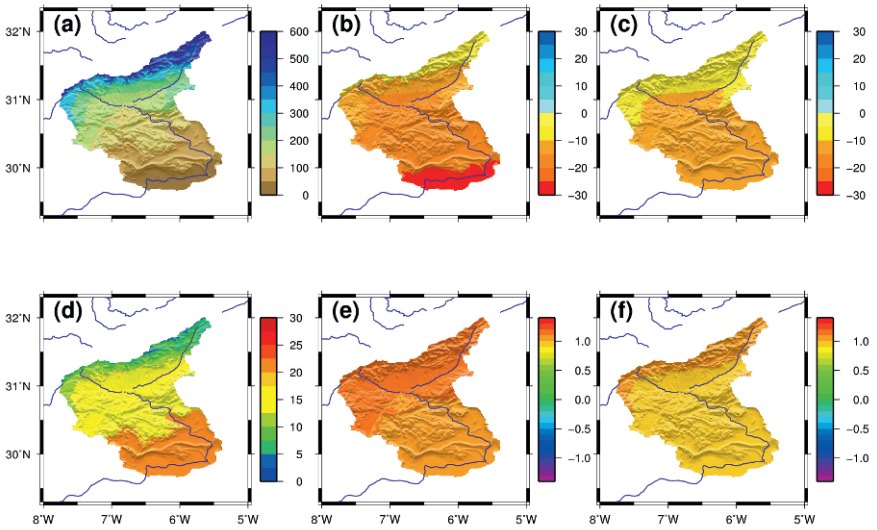

Fig. II-3.2.8: Regional downscaling of climate scenarios. Top row: Annual mean rainfall for (a) present day climate (1960-2000, in mm), (b) difference scenario SRES A1B (2011-2050) minus present day (in percent of the present day climate value), and (c) scenario B1 (2011-2050) minus present day climate in percent. Bottom row: (d) annual mean 2m-temperature in °C, (e) differences between SRES A1B minus present day in °C, and (f) differences between SRES B1 minus present day.

Some additional results pertinent to the impact studies described in chapter II-5 are the decrease in the return periods of extremely dry hydrological years (September-August) whereas the return periods of wet years remain unchanged until the middle of the 21st century (Born et al. 2008b). In spite of the drying trend suggested by REMO, the statistical downscaling of daily rainfall from this model hints at an increase in extreme daily rainfall in the High Atlas Mountains. In contrast, days with extreme rainfall may occur less often at the Saharan foothills of the Atlas Mountains.

II-3.2.7 The statistico-dynamical downscaling approach using circulation weather types: An example for the High Atlas region

In the Atlas Mountain chains, long-term station records of meteorological variables are rare, and the station density is very low (see sect. I-4.3). As a consequence of the orography and the sparse station data, gridded products like the CRU temperature and rainfall data sets have an exceptionally low quality in the northwest African mountain chains. Thus, the application of model error correction and Weather Generator techniques, which both require the use of observational data, is limited. An alternative approach is statistico-dynamical downscaling, comprising a recombination of meteorological parameters stemming from a fixed number of different model episode simulations (e.g., Fuentes and Heimann 2000). These episodes cover a set of distinct circulation weather types that have been identified for the region from large-scale flow patterns. For example, episodes of westerly flow have been simulated using a high-resolution (i.e., 3 km) meteorological model to obtain a physical-based distribution of precipitation in the Drâa catchment area. In the following sections, this regionalization method is outlined, and its advantages and limitations are discussed. For more details see Piecha (2009).

Identification of Circulation Weather Types (CWTs)

The statistico-dynamical downscaling method in this case utilizes the physical relationship between the mean sea-level pressure fields on the synoptic scale (i.e., on spatial scales of several hundreds to thousands of kilometers) and precipitation on the mesoscale (i.e., on spatial scales of several kilometers). The mean sea-level pressure fields are used to identify so-called CWTs (Circulation Weather Types, for further reading: Jones et al. 1993). CWTs categorize pressure fields into eight wind direction types and two circulation types (cyclonic and anti-cyclonic). The frequency of occurrence of the CWTs is shown in figure II-3.2.9.

Overall, the most frequent CWTs in 2002 is “northeast”, indicating that low-level winds from a northeasterly direction are prevalent. The CWT northeast occurs mostly during the summer, but is rare in winter. Taking into account that in the area of the Drâa catchment precipitation (not shown here) peaks in the transitional seasons (see Born et al. 2008a), it is to be expected that the CWT northeast is not responsible for most of the precipitation throughout the year. The CWTs mainly responsible for the precipitation are the cyclonic and southerly flows. The latter can transport moisture into the region from the tropical and subtropical Atlantic Ocean (Knippertz 2003a, 2003b). Neither occurs as frequently as the CWT northeast.

The frequency of the CWTs, combined with information about precipitation behavior within the different CWTs, is used for the statistical part of the downscaling procedure. For the dynamical part, representative dates for the different CWTs are chosen, and the output of the LM at a spatial resolution of 7 km x 7 km

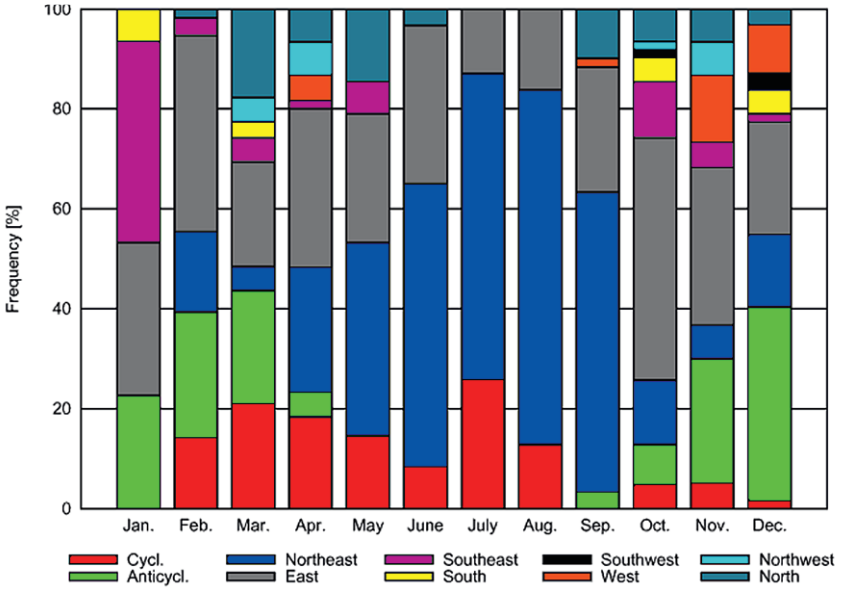

Fig. II-3.2.9: CWT distribution for 2002 by month.

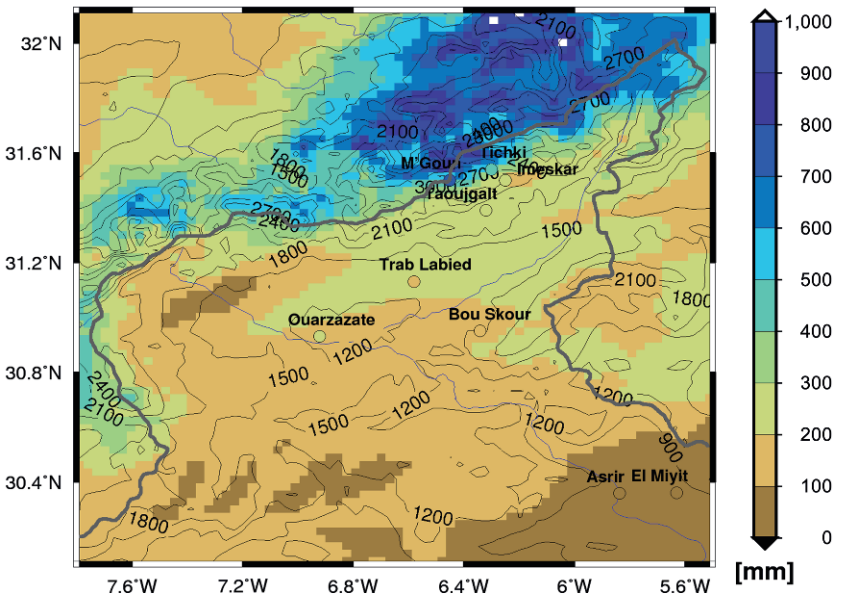

Fig. II-3.2.10: Recombined distributions of precipitation for 2002. The gray line is the border of the Drâa catchment; black lines are the orographic heights in m. The colored dots indicate measured precipitation at IMPETUS stations (cf. sect. I-4.3).

is used to force the FOOT3DK model. The LM was forced by observation at its lateral boundaries. Since the LM run is available for only fourteen months, the different CWTs are grouped into six classes to obtain a larger number of representatives: cyclonic, anti-cyclonic, northeast and east, southeast and south, southwest and west, northwest and north. Representatives with and without precipitation for each CWT group are then simulated with FOOT3DK. A further constraint was the limited computer capacity. Therefore, the 24-hour simulations were run for 23 representatives at a resolution of approximately 3 km x 3 km for the region, as shown in figure II-3.2.10. These 23 episodes occurred between November 2001 and December 2002. This is the physical part of the downscaling.

FOOT3DK output is recombined with the information of the CWT frequency to spatially highly resolved distributions of precipitation or evaporation. The recombination itself operates with an accumulation of the precipitation or evapotranspiration of the representatives per grid-point and given period (for further reading: Huebener and Kerschgens 2007).

For 2002, the results are shown for recombined precipitation in figure II-3.2.10. The precipitation displays the expected north-south distribution with higher values on the northern flank of the High Atlas Mountains and drier conditions south of the main divide. The recombined accumulated precipitation sum and the measurements taken at the IMPETUS stations are in good agreement (see fig. II-3.2.10, colored dots). Bearing in mind that this is a comparison of a point measurement and the mean precipitation of a 9-km² grid, we cannot expect a perfect fit. By in-

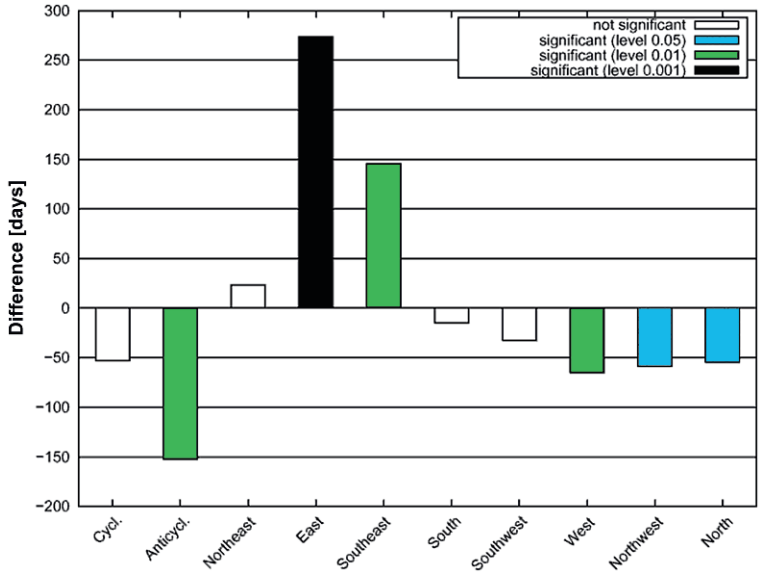

Fig. II-3.2.11: Difference in days of the occurrence of the CWTs in all three REMO ensemble members of the A1B scenario (2020-2049) and the control period (1970–1999). The statistical significance given in the upper-right box is based on a two-sided χ^2 cross tabulation test.

spection of figure II-3.2.10, it can also be concluded that the method is capable of reflecting the orographically modulated annual precipitation in 2002, especially the role of the Atlas mountain crest as a weather divide.

Assuming that the physical relation between the large-scale flow and the local meteorological variables is not affected by the Climate Change, any change in the latter can be assessed by statistically significant changes in the CWT distribution in climate model simulations. The future changes in CWT distribution have been assessed based on REMO mean sea-level pressure data for the SRES scenarios A1B and B1 for the period 2036-2050. The reference period is 1986-2000.

In figure II-3.2.11, the significant changes in the CWT distribution for A1B are shown. The most remarkable feature in figure II-3.2.11 is the statistically highly significant increase in CWT east and CWT southeast. This is consistent with a northeastward shift of the Azores High found in ECHAM5 and in many other IPCC AR4 global models. As a consequence of the change in frequency of occurrence of the CWTs in the A1B scenario, the recombined precipitation shows a statistically significant increase in annual precipitation for the period 2020-2049 in the Djebel Saghro Mountains and large parts of the Ouarzazate Basin (see fig. II-3.2.12). Due to a decrease in westerly flow and cyclonic weather types, rainfall decreases north of the High Atlas Mountain chain and in the Antiatlas Mountains, including the Djebel Siroua massif.

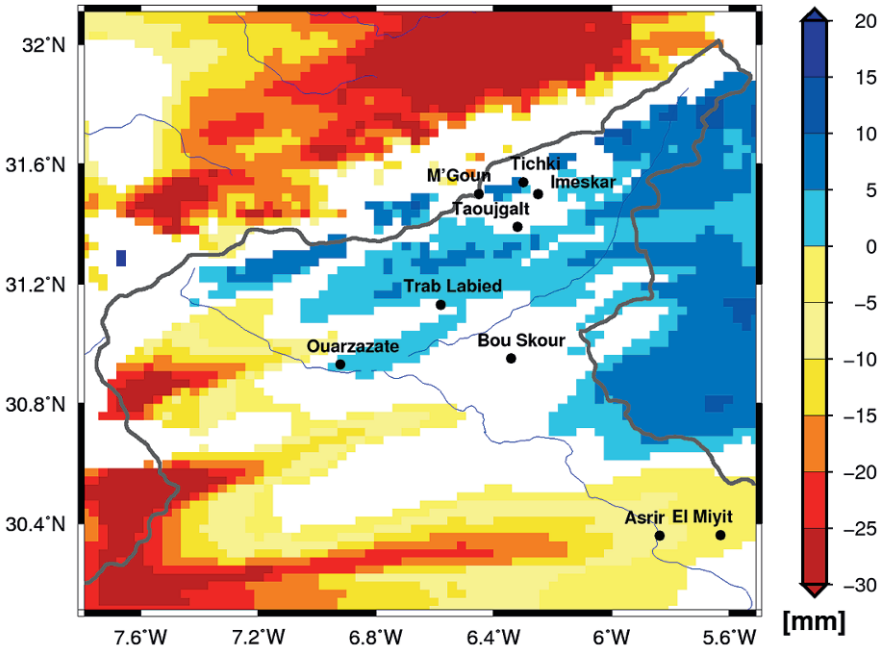

Fig. II-3.2.12: Difference in annual precipitation in all three REMO ensemble members of the A1B scenario (2020–2049) and the control period (1970–1999). Only statistically significant changes based on a two-sided student-t test are plotted in color.

II-3.2.8 Summary of the model-based methods of regionalization of climate information for climate scenarios

All state-of-the-art regionalization methods utilized in IMPETUS, such as dynamical downscaling, statistico-dynamical, and statistical approaches, have been used for the model-based generation of regional scenarios.

For Benin, where a relatively good coverage of station data was available over many decades, we conclude that the application of the bias-corrected regional model, as well as the use of Weather Generators, is the most suitable approach. Regional models, in general, have difficulty simulating the spatio-temporal distribution of rainfall. However, it can be assumed that they provide a reasonable Climate Change signal in the larger-scale (thermo-) dynamic fields (e.g., wind and temperature). The bias-correction and the Weather Generator use the observed statistical distribution and their moments to (a) correct model bias in precipitation and (b) to downscale the Climate Change signal in precipitation to a single station. Moreover, the IMPETUS regional modeling results suggest the consideration of the projections of continental land use changes and vegetation degradation in the regional model scenario runs.

In Morocco, the paucity of station data and the relatively low quality of gridded products (e.g., CRU data) suggest that the bias-correction and Weather Generator approach shall be complemented by alternative downscaling methods. In the mountainous region of the High Atlas, the statistico-dynamical approach using circulation weather types is a promising alternative approach. This method, for example, suggests a somewhat wetter climate for the coming decades south of the High Atlas Mountains – a trend that is contrary to the IPCC global model and the REMO projections. However, such a scenario was deemed to be plausible due to the strong contribution of tropical-extratropical interactions to the annual rainfall on the Saharan flank of the Atlas Mountains (see sect. I-5.2). This method has its own uncertainties. The most noteworthy are likely the selection and number of the representatives and the assumption that the mean local rainfall distribution within a given CWT does not change from to the present climate to the future climate.

If project resources permit, the IMPETUS experience suggests using a variety of regionalization methods to assess plausible and physically consistent pathways of future climates. It is desirable, in any case, to use climate projections from an ensemble of several models. The use of different greenhouse-gas emission scenarios is obsolete if projections are made for the next two to three decades. Finally, we anticipate that the variety of regionalization approaches applied in IMPETUS will remain state-of-the-art techniques for a number of years. The reasons for this lie in the sustained deficiencies in model physics and computer power limitations that both cause substantial biases in global and regional models.

References

Ali A, Lebel T (2009) The Sahelian standardized rainfall index revisited. Int J Climatol. doi:10.1002/joc.1832

Born K, Piecha K, Fink A (2008a) Shifting climate zones in the Northwestern Maghreb. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 13-14. Department of Geography, University of Bonn, Bonn

Born K, Fink A, Paeth H (2008b) Dry and wet periods in the northwestern Maghreb for present day and future climate conditions. Meteorol Z 17:533–551

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 847-940. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The importance of land-cover change in simulating future climates. Science 310:1674-1678

Fink AH, Reiner A (2003) Spatio-temporal Variability of the Relation between African Easterly Waves and West African Squall Lines in 1998 and 1999. J Geophys Res. doi:10.1029/2002JD002816

Fink AH, Vincent DG, Ermert V (2006) Rainfall Types in the West African Soudanian Zone during the Summer Monsoon 2002. Mon Weather Rev 134(8):2143-2164

Fuentes U, Heimann D (2000) An improved statistical-dynamical downscaling scheme and is application to the Alpine precipitation climatology. Theor Appl Climatol 65:119-135

Hagemann S (2002) An improved land-surface parameter data set for global and regional climate models. Max Planck Institute, Report No 336, Hamburg

Hansen JA, Emanuel KA (2003) Forecast 4D-Var: Exploiting Model Output Statistics. Q J Roy Meteor Soc 129:1255-1267

Helmer EH, Ruefenacht B (2005) Cloud-free satellite image mosaics with regression trees and histogram matching. Photogramm Eng Rem S 71(9):1079-1089

Huebener H, Kerschgens M (2007) Downscaling of current and future rainfall climatologies for southern Morocco. Part I: Downscaling method and current climatology. Int J Climatol 27:1763-1774

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Jacob D (2001) A note to the simulation of the annual and interannual variability of the water budget over the Baltic Sea drainage basin. Meteorol Atmos Phys 77:61-74

Jones PD, Hulme M, Briffa KR (1993) A comparison of lamb circulation types with an objective classification scheme. Int J Climatol 13:655-663

Knippertz P (2003a) Niederschlagsvariabilität in Nordwestafrika und der Zusammenhang der großskaligen atmosphärischen Zirkulation und der synoptischen Aktivität. In: Kerschgens M, Neubauer FM, Pätzold M, Speth P, Tezkan B (eds), Mitteilungen aus dem Institut für Geophysik und Meteorologie der Universität zu Köln, Vol. 152, pp. 136. Köln

Knippertz P (2003b) Tropical-extratropical interactions causing precipitation in Northwest Africa: Statistical analysis and seasonal variations. Mon Weather Rev 131:3069-3076

Le Barbé L, Lebel T, Tapsoba D (2002) Rainfall variability in West Africa during the years 1950-1990. J Clim 15:187-202

Lebel T, Delclaux F, Le Barbé L, Polcher J (2000) From GCM scales to hydrological scales: rainfall variability in West Africa. Stoch Env Res Risk A 14:275-295

New M, Hulme M, Jones P (2000) Representing twentieth-century space-time climate variability. Part II: Development of 1901-96 monthly grids of ter-restrial surface climate. J Climate 13:2217-2238

Paeth H, Born K, Jacob D, Podzun R (2005) Regional dynamic downscaling over West Africa: model evaluation and comparison of wet and dry years. Meteorol Z 14:349-367

Paeth H, Born K, Girmes R, Podzun R, Jacob D (2009) Regional climate change in tropical Africa under greenhouse forcing and land-use changes. J Climate 22:114-132

Paeth H (2010) Postprocessing of simulated precipitation for impact studies in West Africa – Part I: model output statistics for monthly data. Clim Dyn doi:10.1007/s00382-010-0760-z

Piecha, K (2009): Statistisch-dynamische Regionalisierung von Niederschlag und Evapotranspiration für den Hohen Atlas in Marokko. Doctoral thesis at the Department ("Fakultät") of Mathematics and Natural Sciences of the University of Cologne. 122 pp., online available at: http://kups.ub.uni-koeln.de/volltexte/2009/2923/ , Accessed 16 March 2010

Roeckner, E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornblueh L, Manzini E, Rhodin A, Schlese U, Schultzweida U, Tompkins A (2003) The atmospheric general circulation model ECHAM5. Part I: Model description. Max-Planck-Inst. f. Meteor., Report No. 349. Hamburg

Xu CY(1999) From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. Prog Phys Geog 23(2):229-249

Zeng N, Hales K, Neelin JD (2002) Nonlinear dynamics in a coupled vegetation-atmosphere system and implications for desert-forest gradient. J Climate 15:3474-3487

II-3.3 Socio-economic scenarios

B. Reichert and A. Jaeger

Abstract:

The approach for the development of regional socio-economic scenarios is presented. Based on process understanding, expert knowledge and an intensive stakeholder dialogue, three alternative scenarios are developed for the river catchments and their sub-regions under investigation. The socio-economic scenarios, which do not take into account Climate Change, describe the general societal, economic and ecological characteristics and the main driving forces. Tables of scenario characteristics give an overview. Serving as the common reference basis for the scenario simulations within IMPETUS, the qualitative and narrative storylines are given in detail. They are written in a way that not only the scientist can derive their specific drivers for their model simulations, but also to enhance understanding and facilitate communication with the targeted stakeholders.

Keywords: Storylines, scenario characteristics, society, economy, ecology, process understanding, stakeholder

II-3.3.1 Introduction

Scenarios help to describe potential future problems and to consider alternatives in the context of uncertainties. Furthermore, they might help to improve our common understanding of problems, to detect and to test our assumptions and to identify useful problem-solving approaches. Scenarios enable us to combine the analysis of long-term development of the natural environment (in this case, water) with the analysis of long-term impacts of political programs and measures. At the same time, scenarios help us to better understand the mutual relationships between the national, regional and local levels.

Scenario analysis has become a common state-of-the-art tool in support of environmental decision-making (e.g., Marsh 1998; Ringland 1998; Shackley and Deanwood 2003; Leney et al. 2004; UNEP 2005; Carpenter et al. 2006; Alcamo 2008; Mahmoud et al. 2009). Scenario analysis with either independent development of socio-economic and climate scenarios or 'co-evolutionary' (Lorenzoni et al. 2000) scenario techniques is widely used in interdisciplinary water resources research projects (e.g., Gaiser et al. 2003; Shackley and Deanwood 2003; Means et al. 2005; Carpenter et al. 2005; Alcamo 2008; Lui et al. 2008).

In the framework of the IMPETUS project, three socio-economic scenarios were developed for both Benin and Morocco in addition to the three climate scenarios (see sect. II-3.2). Being formally independent both scenario sets permit a clearer distinction between the effect of physical Climate Change and socio-economic change (e.g., Shackley and Deanwood 2003). Unlike to Mahmoud et al. (2009), which restrict socio-economic scenarios to 'demographic driving forces and the sensitivity, adaptability and vulnerability of socio-economic conditions', the IMPETUS socio-economic scenarios encompass future environmental factors and conditions, and technological changes affecting societal and environmental growth besides economic, political, and societal factors. The time range for the two catchments, up to 2020 for Morocco and up to 2025 for Benin, differ due to pre-existing long-term strategy papers of the respective governments (*Bénin 2025: ALAFIA, Stratégies de développement du Bénin à long terme, Minist. de Coord. Plan. Devel. Empl.,* (PNUD 2000); *Stratégie 2020 de développement rural, Document de Référence* (Conseil Général du Développement Agricole au Maroc 1999). The temporal resolution is five years. As described in section II-3.1, each river catchment was spatially divided into three homogenous scenario sub-regions according to its demographic, economic, and natural framework (see sect. II-3.1, fig. II-3.1.1).

As the analysis of future water availability requires a sound understanding of the current processes of the various aspects of the hydrological cycle, all disciplines contributed significantly to the scenario development with the necessary

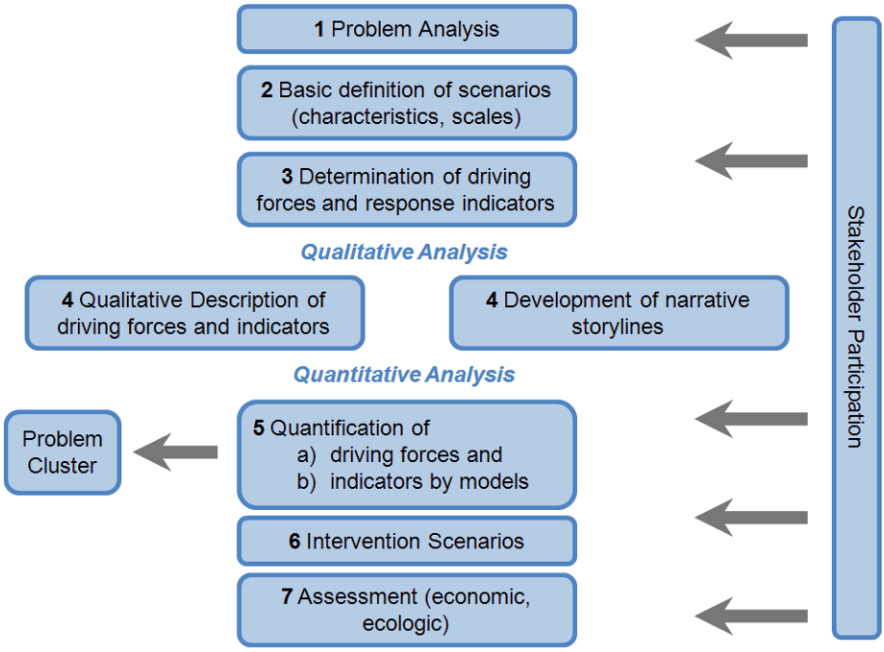

Fig. II-3.3.1: Overview of the scenario development process in the IMPETUS project.

input. Involvement of stakeholders from the beginning of the process helped to create convincing descriptions of alternative futures and prevented scientists from incomplete or even incorrect valuation of certain driving forces or response indicators. Furthermore, stakeholder participation throughout the process might assure the subsequent use of the socio-economic scenarios. The structure of the scenario development process is given in figure II-3.3.1.

Scenario development started with the definition of the main characteristics and spatial scales of the scenarios (see sect. II-3.1, fig. II-3.1.1). Furthermore, the main drivers and their respective response indicators were selected and qualitatively described in a so-called 'qualitative trend-matrix'. As economic, social and environmental developments influence the availability of fresh water, the 'qualitative trend-matrix' covers all key aspects, with around 80 variables for each country. Based on this broad data set, with contributions from all disciplines and the input of the stakeholders, the narrative storylines of the socio-economic IMPETUS scenarios were woven by a smaller group of scientists.

Quantification of both climate and socio-economic scenarios was performed in the context of the various problem clusters with a set of suitable models, either numerical or expert (see chapt. II-1). Almost every discipline adapted existing models to the targeted regions. In order to solve the multidisciplinary questions of the problem clusters, the disciplinary models were often loosely coupled in several spatial decision support systems (SDSS) (see sect. II-2.1). A full coupling of two numerical models as given within the SDSS PEDRO was one of the few exceptions (see subsect. II-2.4.1). Hence the qualitative storylines give the descriptive guidance on the quantification; each researcher had to define the socio-economic key factors for his simulation models (e.g., Jakeman et al. 2006; Nguyen et al. 2007; Scholten et al. 2007). Assessment of the scenarios was performed by either qualitative or quantitative response indicators (for details, see the following chapters).

With the two last steps of the scenario analysis (see fig. II-3.3.1), the three socio-economic scenarios of each country were refined by simulating various measures in the intervention scenarios to compare their effects on water availability in the future projections. Measures vary between political decisions, such as changes in fertilizer policy (see sect. II-4.1: tax exemption of fertilizer in Benin), and technological modification of agricultural practices (see sect. II-4.2: drip versus traditional flood irrigation in Morocco).

II-3.3.2 IMPETUS scenarios for the Ouémé catchment, Benin

The three socio-economic scenarios for the Ouémé catchment in Benin can be briefly described as follows:

B1: *Economic growth and consolidation of decentralization*

B2: *Economic stagnation and institutional insecurity*

B3: *Business as usual*

With B1, a scenario is developed, which describes a future of political stability and economic growth. Living conditions of the population improve, and the overall pressure of resource depletion decreases due to technical innovations. B2 sketches the opposite path. The influence of a continuing and mutually reinforcing downward spiral of political destabilization and economic depression leads to negative overall economic development, which also undermines the political stability of the country. Living conditions worsen or stagnate at a low level. Resource depletion and resulting conflicts increase. In B3, the current trends persist. The country is successful in maintaining its political stability, but economic development and social welfare do not improve in general. Population growth continues to decline, and the traditional power structures on the local level remain rather unchanged. The overall characteristics of the three scenarios are presented in table II-3.3.1. The variability within the spatially differentiated scenario sub-regions (Upper Ouémé: rural, low population density, one annual rainy season; Middle Ouémé: rural, southern border of transhumance; Lower Ouémé: high rate of urbanization, high population density, well-developed infrastructure, two annual rainy seasons; see sect. II-3.1: fig. II-3.1.1) is described in the following storylines.

Storyline for socio-economic scenario B1: *Economic growth and consolidation of decentralization*

Foreign direct investment increases, and new marketing opportunities in regional markets are developed. Traffic infrastructure is extended; Benin strengthens its role as a transit country. Continuity in the coupling of CFA with the Euro leads to high monetary stability. The country succeeds in improving its competitive position on international markets. Export revenues continue to be generated by the agriculture sector with the export of raw and, especially, processed products. However, agriculture maintains its key position in the country's economy. Transfers from development cooperation remain largely unchanged. More 'public-private partnerships' are developed.

Innovation rates in the agricultural sector increase, and agricultural areas expand in total. World market prices for major export products remain stable at a low level. Institutional innovations regarding the organization of agricultural farms, their distribution channels and technical innovations for processing of agri-

Table II-3.3.1: Characteristics of the socio-economic scenarios for the Ouémé catchment, Benin.

Scenario B1: Economic growth and consolidation of decentralisation	**Scenario B2:** Economic stagnation and institutional insecurity	**Scenario B3:** Business as usual
Main economic framework conditions		
- Constant growth - Deeping of international competitiveness - Growing importance of industrial sectors - Consolidation of the role as a transit country	- Economic stagnation - Decoupling of global markets - Loss of international competitiveness - Declining incomes - Loss of the role as an important transit country	- Strong informal and weak formal economic integration - Low competitiveness on world markets
Agriculture sector		
- Increasing rate of innovations - Expansion of agriculture areas - Increase in processing of agricultural products - Increase in exports	- Missing innovations - Stagnation of productivity - Increase of substistence farming	- Low rate of innovations - Expansion of agriculture areas and livestock farming
Political framework conditions		
- Political stability - Functional decentralized administrative structures - Development cooperation continues - Foreign investments increase	- Political destabilization - Dysfunctional decentralized administrative structures - Increasing societal conflicts - Decline of development cooperation	- Established societal power structures prevail - Small improvements - Development cooperation continues, but with main focus on poverty reduction
Demographic framework conditions / Living quality		
- Accelerated decline of population growth - Growth of regional cities - Improvement of living conditions - Rise in overall level of education	- Slow decline of population growth - Deterioration of living conditions	- Continued decline of population growth - Growth of regional cities - Migration into foreign countries - Slight improvement in basic needs supply
Environment and resources		
- Management strategies are implemented - Resources conflicts decline - Water use increases	- Uncontrolled exploitation and use of resources - Resource conflicts prevail - Weak resource management	- Resource conflicts due to shortages - continued resource management

cultural products enable a diversification of production strategies and an expansion of the product range. Technical innovations, like mechanization, and the increased utilization of fertilizers further increase productivity. The agricultural sectors win market shares in regional markets and increase their export rates. The processing of primary agricultural products leads to added value. Projections differ between the three sub-regions. While, in the Upper Ouémé, agricultural areas are expanding significantly, expansion is only marginal in the Middle Ouémé and remains unchanged in the Lower Ouémé.

Administrative reforms started in the context of democratization and decentralization show promising results. In particular, measures of anti-corruption, better access to information and stronger public control of political decision-makers result in a reduction of the abuse of authority and crime. Funding policies for local initiatives increase. However, the traditional power structures and the related problems of overlapping political competencies do not change. The enduring internal political stability leads to a continuation of international development cooperation. Benin is able to close several international treaties of cooperation. Those funds stabilize the expansion of water and energy supply, canalization, transport infrastructure and education. The population growth rate declines much faster than originally expected due to lower fertility rates and a stronger integration of women into the labor market. Higher and Middle Ouémé are exceptions due to the continuing immigration from their northern neighbors. Urbanization proceeds in the Lower Ouémé.

The quality of life increases in many regions. Basic supplies of water, food and energy, but also the quality of education and security, improve. Accordingly, the level of education rises. The strongest growth rates happen in Upper Ouémé, but this region also has the lowest starting level. Improved basic living conditions lead to a reduction of epidemics.

Progress in the agricultural sector, better education and specialization of the work force, as well as the improvement of living standards cause a decline in the exploitation of natural resources. Better capacities for more effective, broader resource management are developed, and societal conflicts about scarce resources diminish. Forest protection and management gain greater importance. National water strategies are implemented and improve the water supply. Water use increases in all sectors. The illegal timber industry is declining due to the continuing expansion of agricultural areas and better administrative control. Reforestation measures become more lucrative and are therefore more often executed.

Storyline for socio-economic scenario B2: *Economic stagnation and institutional insecurity*

Declining world market prices for Benin's main export products, such as cotton, lead to a decrease of export revenues. The resulting shortage of foreign currencies reduces the availability of support programs for the private sector. Technical pro-

gress and economic growth stagnate. The international competitiveness of the country drops and inflation increases. The economy of Benin disconnects more and more from the international markets, and intraregional economic integration with neighbor countries fails on a large scale. Reduced transit minimizes proper delivery, even to markets of neighbor countries with open borders, driving further economic downturn. Regional economic cooperation runs dry. Accordingly, the average income of the population declines. Lower Ouémé suffers from the declining importance of the Cotonou port. This impairment is caused especially by the weak economic development and the weakening of the overseas import and export business. Insufficient capacities for complying with international norms and standards add to the overall economic unattractiveness of the port.

Agriculture maintains its role as the main source of income and employment. However, innovation rates are low and productivity declines. The farmers try to compensate for this development by expanding the agricultural areas, but the lack of capital for the targeted acquisition of fertilizer and seeds, the absence of draft animals and other technologies, and also the lack of qualified agricultural advisory services almost entirely impede increasing productivity. Subsistence farming gains importance due to limited agricultural modernization and instability of alternative employment strategies. The stagnation of infrastructure development causes a worsening of access conditions for farmers to markets. Labor force demand is met by greater rates of immigration.

The worsening of living conditions leads to civil uproar, triggering increasing political destabilization of the country. Due to the growing corruption within the administration, legal relationships become insecure, and the citizens' credibility and trust in public administration is shattered. As a result, international donors withdraw their support; Benin loses its status as a main focus country of international development cooperation. The turmoil precipitates violent conflicts. Decentralized administrative structures prove to be dysfunctional. Missing capacities and susceptibility to corruption prevent sufficient implementation of policies and programs. Political parties and the administration lose public trust and watch helplessly as the rate of conflicts increases. Non-governmental organizations gain importance. Also, individual civil engagement becomes more and more important. The general population growth slows down marginally. Especially in rural areas, mortality increases in years of crisis. AIDS, malaria, and plagues become more frequent.

The availability of agricultural areas and the demand for workers in this sector make Upper Ouémé an attractive target for migrants from other regions. The growing demand for family workers narrows the success of family planning programs that had contributed to the decrease of population growth. The rate of child mortality is high due to insufficient basic medical treatment. This leads to an increase of the birth rate. The regional population in Upper Ouémé grows due to immigration, both internally and from neighbor countries. The strong demand for agricultural workers and the lack of alternatives in cities slow down the urbanization of the region. Unlike in the north, population growth rates in Middle Ouémé are

declining. Work migration into neighbor countries, but also into Europe, proliferates. There is a similar picture in Lower Ouémé, but the rate of emigration is higher due to the scarcity of agricultural areas. The most common target regions for migration are Upper Ouémé and Nigeria.

Quality of life declines in all sub-regions. The degradation of natural resources, the decline of development cooperation and growing conflicts reduce the capability of greater proportions of the population to cope effectively with crises. The supplies of medical care, education, energy, water, and food are inadequate. Local authorities cannot ensure resources for maintaining their area's infrastructure. Economic activities are reduced to satisfy basic needs in many regions.

The increased pressure on natural resources triggers conflicts between different users over scarce resources, especially in the Upper Ouémé. Here, conflicts arise between livestock farmers and crop producers. While in Middle Ouémé the conflicts rise between autochthons and immigrants, agriculture and housing development are the focus of conflicts in Lower Ouémé. In all regions, uncontrolled land use leads to deforestation. This aggravates the process of soil degradation. Water use remains relatively steady. The administration is not able to secure functioning resource management due to missing capacities. Accordingly, they are also unable to moderate user conflicts.

Storyline for socio-economic scenario B3: *Business as usual*

Agriculture maintains its role as the key economic sector; industry and service stagnate. Regional exports remain at a low level with large fluctuations. Due to weak formal economic integration, informal economic activities gain importance, mainly for securing individual livelihood. The country remains dependent on the revenues from informal transit export and export of agricultural goods, which are subject to large price fluctuations on world markets.

Agricultural areas and livestock farming are extended. However, the resulting increase in agricultural productivity is smaller than expected due to lower innovation rates. Intensive livestock farming gains importance in all regions. In Upper Ouémé, cultivation of cashew, cassava, yams and maize is moderately increased. Productivity will increase through increased use of fertilizers and pesticides and continuing mechanization. Expansion of agricultural areas increases strongly in Middle Ouémé. However, the fragmentation of land due to partition continues. The development in Lower Ouémé is different; agricultural area is not expanding in this region. A stronger differentiation of the production of single plants takes place (pineapple, teak, vegetables). Areas formerly used for the production of oil palms are converted into production areas for maize and cassava. The already widespread use of fertilizers and pesticides is increased. Comparable to Middle Ouémé, the fragmentation of agricultural areas takes place through partition, but also through speculation.

Established power structures remain constant in the decentralized administrative units. Local structures continue to exist. The number of non-governmental organizations increases, but this does not automatically lead to an upgrade of their political influence. New responsibilities, and subsequently new actors, are also created in local administration. These new responsibilities partly overlap according to the policy area, which creates competition between decision-makers in the old and new political arenas. Ineffective administrative structures are the result, especially on the lower administrative levels. Administration is not very effective in all three regions, but there are continuous efforts to improve its efficiency. International development cooperation maintains its substantial importance and has a strong impact on all economic sectors.

The general population growth rate declines. More and more workers migrate into neighbor countries. Within Benin, the Upper Ouémé is the most important target region for inter-rural migration, mainly by peasants coming from Middle and Lower Ouémé. Accordingly, the population in this region grows larger than in the two other regions. Medical care is improved, and the rates of child mortality, postnatal mortality and malaria infections decline slightly but remain at a high level. The basic needs of the population (water, energy, medical care, and education) remain unsatisfied in all three regions.

Increased scarcity of resources can be observed in all three regions. This triggers conflicts between different user groups. However, programs for resource protection continue. Water use grows in private households but stays constant in industry and agriculture. In rural areas, water management remains insufficient. Resource conflicts between crop farmers and livestock farmers continue to exist. Water use increases in Lower Ouémé due to greater urbanization.

II-3.3.3 IMPETUS socio-economic scenarios for Morocco

In order to investigate the effects of global and regional change on the societal, economic and environmental conditions and thus their influence on the water resources for the Drâa catchment in Morocco, the following three contrasting scenarios were developed:

M1: *Marginalization – non-support of the Drâa region*

M2: *Rural development through regional funds*

M3: *Business as usual*

The scenario M1 describes a scenario of stagnation and marginalization in the industrial, agricultural, and tourist sectors due to withdrawal of the support of governmental and international institutions. As a result, the marginalization of the region and the impoverishment of the local population accelerate and work migration increases. M2 gives the opposite picture, where the Drâa catchment profits from national funding, which leads to increased productivity in the agricultural

sector, strong growth of tourism, and a decrease of migration due to alternative income possibilities. Furthermore, more sustainable use of natural resources, including water and pastures, is possible. Projection of the current trend into the future with scenario M3 shows that industrialization persists at a low level and tourism is restricted to individual tourism in selected areas. Agriculture continues to dominate the economy, but its further expansion is constrained by water scarcity and low-level techniques. Population growth is high in a few urbanized areas despite high rates of work migration and childhood mortality.

The general characteristics of the three scenarios are given in table II-3.3.2 and in the following narrative storylines. The variability between the sub-regions of the Drâa catchment is briefly discussed in the storylines. As described in section II-3.1, the three regions considered are: the High Atlas (marginalized mountain region with poorly developed infrastructure and good water availability), the Basin of Ouarzazate (well developed infrastructure and good water availability), and the Oases south of the El Mansour Eddahbi Dam (low water availability; agriculture is dependent on the management of the dam) (see sect. II-3.1; fig: II-3.1.1).

Storyline for socio-economic scenario M1: ***Marginalization - non-support of the Drâa region***

Existing differences in Morocco between urban and rural regions and between growth areas and marginalized areas deepen as a result of the national policy. The Drâa region is neglected and largely exempted from funding. Consequently, its marginalization continues. Due to withdrawal of governmental support, the traditional decision processes gain importance. However, the potential for conflict rises because individualization of economic actions increases at the expense of community solidarity. Institutions supporting rural development close down. The Drâa region is unattractive for investors due to its underdeveloped infrastructure and low degree of industrialization. Public funding agencies withdraw their engagement on a large scale, which leads to further marginalization of the region. Economic growth loses further momentum, investments into the infrastructure cannot be maintained, and accordingly, the infrastructure lapses.

Industry is still limited to the Ouarzazate Basin, where it stagnates and partly declines. Minor growth of the construction sector and a significant upturn in the informal sector occur. Tourism does not provide a basis for sustained economic development. In the High Atlas, only trekking tourism as an economic niche becomes important, whereas in the Ouarzazate Basin, the decline of the infrastructure leads to a substantial decrease of tourism. Desert tourism in the oases stagnates on a low level.

The importance of subsistence farming continues due to lacking employment alternatives. The amount of agricultural area stays largely constant. Productivity remains at a low level, partly due to the persistent low-level techniques used. Resources for research and agricultural advisory services are lacking. The production

Table II-3.3.2: Characteristics of the socio-economic scenarios for the Drâa catchment, Morocco.

Scenario M1: Marginalisation – non-support of the Drâa-Region	**Scenario M2:** Rural development in the Drâa-Region through regional funds	**Scenario M3:** Business as usual
Main economic framework conditions		
- Region does not profit from economic upswing - Industry remains marginal - Stagnation of tourism	- Programs for„self-aid" - Increase of tourism	- Low rates of industrialisation - Slow increase of tourism, mainly individual in selected areas
Agriculture sector		
- Missing innovations - Agriculture areas and livestock farming remains constant - Stagnation of productivity	- Increasing rate of innovations and productivity - Cash-Crops for regional markets - Reduction of livestock farming	- Low rate of innovations - Expansion of agriculture areas and livestock farming
Political framework conditions		
- Funding programs decreases - Traditional mechanisms of decision-making gain importance at local level	- Intensification of support programs (according to strategy 2020) - Valorisation of local governance	- Funding programs for tourism only - Dualism of modern and traditional forms of administration
Demographic framework conditions / Living quality		
- Increased migration - Demographic polarisation - Deterioration of living conditions	- Decline of migration - Improvement of living conditions	- High rates of migration - Slight improvement in basic needs supply - Education opportunities improve
Environment and resources		
- Privatisation of water supply (increasing water prices) - Increase of energy costs - Uncontrolled exploitation of resources	- Infrastructure is further extended (water pipelines, sewage treatment plants in cities) - Use of renewable energies - Increase of water use	- Increase of energy costs - Water scarcity limits expansion of agriculture areas

of cash crops is decreasing. They are neither competitive on other regional markets nor on the world markets. In the High Atlas, the amount of agricultural area used mainly for subsistence farming remains constant. The production of cash crops is reduced due to a lack of resources for purchasing seed, fertilizers and pesticides. The poor infrastructure does not allow for meaningful marketing. In the Ouarzazate Basin, the size of farms increases in parallel to the commercializa-

tion of production, but investments into the existing systems of water supply cannot be maintained. However, marketing opportunities are even worse here. Livestock farming remains relatively constant, but declines slightly. Sedentarization of nomads gains importance. Livestock farming in the High Atlas and Ouarzazate Basin stay constant.

Work migration grows. Due to the migrants' support of their families, at least their basic needs are satisfied. Migration leads to demographic polarization, with strong shares of very young and quite old persons. Birth rates and rates of childhood mortality remain high due to the insufficient implementation of health care and family planning programs. In the High Atlas, the population remains high. Emigration toward the economic centers and toward Ouarzazate increases strongly, but is compensated by a strong increase in birth rates. The high rates of migration in the Ouarzazate Basin are partially compensated by internal migration from the two other sub-regions.

Living conditions worsen. It becomes more and more problematic to maintain the regional infrastructure for education and vocational training. Schools decline and teachers are less motivated to work in this region. Costs of education rise substantially. The level of education thus stays low, especially for girls. Schools which teach the Koran become more and more popular.

The privatization of the water supply causes a strong increase of water prices, constraining access to water for part of the population. However, it is primarily the increase of energy prices that has the most important consequences: the population starts to make increasing use of local firewood, which increases the pressure on the natural vegetation. Commercialization and declining public interest trigger a worsening of water management, leading to uncontrolled and unsustainable use of groundwater. The competition between communities in the upper and lower river regions implies a strong potential for conflicts. Water availability is not a problem in the High Atlas, but the supply of drinking water is mainly dependent on the initiative of the local population. In Ouarzazate Basin, the interest of public agencies in functional and targeted water management is marginal. Efficiency of water use in agriculture remains steady. Domestic water use rises. Costs for water extraction (water pumps) increase, mainly due to the rise of energy prices. In the oases, water quality decreases in the two southernmost oases due to lacking funds for infrastructure renewal. Higher energy costs impose increased costs of water extraction in this region also.

Storyline for socio-economic scenario M2: *Rural development in the Drâa region through regional funds*

Societal stability improves in the region in the context of overall positive economic development in Morocco. The economic integration of the global markets for capital, goods, and services proceeds continuously. Globalization triggers positive impulses for economic growth in Morocco. The country profits from strengthened

integration into the European markets. Those revenues enable targeted support of disadvantaged regions like the Drâa region in the context of the governmental Strategy 2020, which is fully implemented. Accordingly, regional institutions like the ORMVAs (*Offices Régionales de Mise en Valeur Agricole*) are strengthened. At the same time, the responsibility of users is increased, which enhances their identification with the program and the effectiveness of its implementation. On the local level, traditional institutions and structures are used to advocate development programs and implement planning processes. New sectors are successfully developed, like the processing of agricultural goods or traditional craftwork. A targeted granting of small credits enables economic independence and a strengthening of the position of women in society. This targeted support reduces dependency on general support schemes and on transfers from migrants.

However, there is no allocation of industry in the High Atlas. In the Ouarzazate Basin and in the oases, economic development concentrates on the extension of processing of agricultural goods. However, the problems of structural deficits in economic development and the overall strong focus on agriculture remain unsolved. Tourism increases in all regions, mainly due to the extension of the infrastructure and the support of regional tourism enterprises. The number and average size of the agricultural areas increase slightly. Also, the productivity of intensive agriculture rises, whereas the importance of subsistence farming is on the decline. Agro-structural funding supports the development of agricultural innovations, like the cultivation of salt-resistant crops or marketable cash crops. Techniques for the improvement of water use efficiency are introduced. There are differences in the development of the agricultural areas of the three sub-regions. In the High Atlas, the agricultural land slightly increases, whereas it stays constant in the other two regions. Furthermore, the Ouarzazate Basin and the oases experience continuous modernization of production techniques. Livestock is further reduced, but nomadism still prevails for parts of the population. Livestock farming in the High Atlas is characterized by a smaller number of cattle per capita, but a higher productivity and thus better income possibilities. The system of rotating pastures is strengthened, allowing more sustainable pasture management. Intensive cattle farming becomes important in the Ouarzazate Basin. The transhumance livestock farming continues to exist, like in the High Atlas, but loses importance. In the oases, nomadism prevails, and livestock farmers are controlled by public authorities with the help of pasture management.

Overall living conditions improve due to alternative income opportunities. Migration rates decline. Educational institutions, especially schools, are expanded through governmental support. Family planning programs are run in parallel and show their first positive results, facilitated through increased literacy rates and better adaptation to local demands. Improved hygienic conditions and good access to medical care result in a decline of childhood mortality and an increase of the population. Furthermore, there are programs to educate farmers about strategies for adaptation in the context of global environmental change. Better hygienic conditions, supply of water, energy, food, housing and medical care, and also the in-

creased educational levels and the success of the family planning programs lead to an increase of the population in the High Atlas, partly brought forward by a decline in migration. In the Ouarzazate Basin and the oases, urbanization also increases with regard to medium-sized cities. The trend toward smaller families is strengthened.

In the High Atlas, public water management concentrates on exploiting drinking water and installation of pipelines. State-driven support for the expansion of these local networks is, however, linked to higher costs for the local population. In the Ouarzazate Basin, water management is oriented toward ensuring the supply of drinking water via pipelines. This generates high investment costs converted to the consumers. To secure the water supply, an exploitation of deep wells and the importing of drinking water from the High Atlas are necessary. The demand for water for irrigation is met through the construction of small reservoirs. In the oases, water management develops along a similar path. Hence, the southernmost oases are confronted with salted groundwater. Long-distance pipelines have to be installed to supply them with water. Securing a sufficient water supply receives more and more attention from public agencies, which implement related measures to improve the situation.

Storyline for socio-economic scenario M3: *Business as usual*

In the Drâa region only tourism, specifically individual tourism concentrated in a few interesting spots, benefits from Morocco's general economic upswing. Subsistence farming remains the most important economic sector. Cash crops are produced solely for regional or national markets. No internationally competitive agricultural products are produced. The industrial sector, including the processing of agricultural products, continues to be of little importance. With the help of national funding and international help programs, infrastructures such as the domestic water supply are further extended, but these improvements are mainly concentrated in tourism centers. Transport connections are improved. Service sectors, especially the informal sector, gain more importance in the medium-sized cities, showing strong growth. Trekking tourism stabilizes at a low level in the High Atlas as the only income source besides agriculture. In Ouarzazate Basin, the processing of agricultural products (roses, saffron) stagnates at a low level. The services sector is expanding substantially in the urban center of Ouarzazate, but also in the other medium-sized centers of the area. This is partly influenced by the increasing investments into tourism. In the oases, money from work migrants is used for purchasing motorized pumps, which are increasingly used for the production (irrigation with groundwater) of Lucerne for local markets. The desert tourism in the south is the main beneficiary of the positive development in the tourism sector.

Due to the continuing dominance of subsistence farming, most farmers continue to be landowners as well. The agricultural area remains constant. Innovations in agriculture, such as improvements of seeds and more effective use of fertilizers

and pesticides are mainly funded by regional organizations, e.g., by the ORMVAO (*Office Régionale de Mise en Valeur Agricole de Ouarzazate*). The mechanization of agriculture does not really increase, mainly due to the many small parcels of irrigated land; only the use of motor pumps increases. Traditional distribution mechanisms nonetheless dominate irrigation agriculture, although they lose importance in some regions as motor pumps promote individualization. The enforcement of individual rights over collective rights is promoted more and more with the help of jurisdiction that is perceived as expensive and corrupt.

In the High Atlas, changes in agriculture remain marginally. Only cash crop production (like apples) for local markets is expected to increase. Agricultural area cannot be extended substantially. Traditional systems of water distribution continue to dominate due to better water availability. Livestock farming continues to be shaped by transhumance, which does not compete with crop farming. Domestic livestock production remains at a low level. In the Ouarzazate Basin, cash crop production stagnates. Transhumant breeders become competitors of livestock owners, especially in the foreland of the Atlas. Agricultural production improves through an increase of immigrants; in addition, the commercialization of agriculture is furthered. In the oases, the production and marketing of dates is declining. Due to the increased number of working migrants and a change of values, especially among young men, a shortage of workers occurs despite the general population growth. Abandonment of agricultural areas is the consequence.

Population grows, driven by a high birth rate. Family planning programs are implemented but are not really successful. Population growth is compensated by growing work migration and a relatively high rate of childhood mortality. The increased rate of working migration leads to manifold changes in family structures. Modern, more urban life concepts gain importance, propelled by better education, especially benefiting girls. The construction of schools improves education possibilities in all regions, but with strong fluctuations in quality.

Water supply in the High Atlas is unproblematic, but water availability is declining toward the south. Urbanization causes a strong increase of water demand in the Ouarzazate Basin. Problems with the water supply are aggravated in the west of the region, mainly due to increasing salinization. In both the Ouarzazate Basin and the oases, public water management remains ineffective. Publicly-initiated institutions are not able to achieve acceptance. The intensive use of water by the upstream riparian reduces the surface water availability in oases. Individual (uncontrolled) irrigation with groundwater using motor pumps leads to a visible decline of groundwater levels in the oases. Overuse of groundwater triggers a salinization of the aquifers in the oases, which supply drinking water.

References

Alcamo J (ed) (2008) Environmental futures: The Practice of Environmental scenario Analysis. Elsevier, Amsterdam

Carpenter SR, Prabhu L, Pingali E, Bennett M, Zurek MB (eds) (2005) Ecosystems and Human Well-being: Scenarios. - The Millennium Ecosystem Assessment series; V. 2. Island Press, Washington DC

Carpenter SR, Bennet M, Peterson GD (2006) Scenarios for ecosystem services: An overview. Ecol Soc 11(1):11-29

Gaiser T, Krol M, Frischkorn H, de Araujo JC (eds) (2003) Global Change and Regional Impacts: Water avilaibility and vulnerability of ecosystems and society in the semiarid northeast of Brazil. Springer, Berlin

Jakeman AJ, Letcher RA, Norton JP (2006) Ten interative steps in development and evaluation of environmental models Environ Modell Softw 23:602-614

Leney T, Coles M, Grollman P, Vilu R (2004) Scenarios Toolkit. Office for Official Publications of the European Communities, Luxembourg

Lorenzoni I, Jordan A, Turner R, Hulme M (2000) A co-evlutionary approach to climate change impact assessment, P: Integrating socio-economic and climate change scenarios. Global Environ Chang 10:57-68

Lui Y, Gupta H, Springer E, Wagener T (2008) Linking science with environmental decision-making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environ Modell Softw 23:846-858

Mahmoud M, Liu Y, Hartmann H, Stewart S, Wagener T, Semmens D, Stewart R, Gupta H, Dominguez D, Dominguez F, Hulse D, Letcher R, Rashleigh B, Smith C, Street R, Ticehurst J, Twery M, van Delden H, Waldick R, White D, Winter L (2009) A formal framework for scenario development in support of environmental decision-making. Environ Modell Softw 24:798-808

Marsh B (1998) Using scenarios to identify, analyze and manage uncertainty. In: Fahey L, Randall R (eds) Learning from the Future, pp. 39-53. Wiley & Sons, New York, NY

Means E, Patrick R, Ospina L, West N (2005) Scenario planning: A tool to manage future water utility uncertainty. J Am Water Works Ass 97(10):68-75

Nguyen, TG, deKok JL, Titus MJ (2007) A new approach to testing an integrated water systems model using qualitative scenarios. Environ Modell Softw 22:1557-1571

Ringland G (1998) Scenario planning. Managing for the future. Wiley & Sons, New York, NY

Scholten H, Kasshun A, Refsgaard JC, Kargas T, Gavardinas C, Beulens AJM (2007) A methodology to support multidisciplinary model-based water management: Environ Modell Softw 22:743-759

Shackley S, Deanwood R (2003) Constructing social futures for climate-change impacts and response studies: building qualitative and quantitative scenarios with the participation of stakeholder. Clim Res 24:71-90

UNEP (2005) Millennium Ecosystem Assessment. http://www.millenniumassessment.org/

II-3.4 Population projections for Benin

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Abstract

Population growth is seen as one of the key drivers of Global Change. At the same time the relation between population dynamics and environmental change is quite complex and linked in many ways and through multiple social and economic mechanisms at various spatial scales. Using demographic data from different censuses since 1979 different population projections were developed that reflect all three socio-economic scenarios and their respective storylines. The methodological challenges of projecting population into the future on various spatial scales are presented exemplarily for three different *départements* and *communes*.

Keywords: demography, population growth, population projections

The demographic dimension of environmental change

Population growth is seen as one of the most important driving factors for environmental change, especially regarding the loss of biodiversity, resource depletion or degradation and the resulting shortages and scarcities (Harrison and Pearce 2000; UN DESA 2001). Population might affect the environment through increasing pressure on marginal lands, over-exploitation of soils, overgrazing or overcutting of wood resulting in soil erosion, silting and flooding. While this looks like a unilinear causality, the relation between population dynamics and environmental change is often far more complex and linked in many ways and through multiple social and economic mechanisms at various spatial scales. The idea that a causal connection between population growth and environmental degradation is questionable is also indicated in conflicting theoretical approaches that take into account, for example, the role of technological change in enabling adaptations and therefore in accommodating more population or political ecology approaches that see both environmental degradation and rapid population growth as consequences of poverty (Blaikie and Brookfield 1987; Jolly 1994; Blaikie 2008; Simon 2008). However, it is obvious that population dynamics remain a key driver and must be taken into account when developing scenarios that provide plausible images of alternative futures but population must be regarded as more than an exogenous variable. With regard to the use of population projections as an input for the set of natural science models within IMPETUS, multi-way linkages between population change

and other elements of the analyzed system must be recognized, and a systemic view of the linkages is therefore needed (Lutz et al. 2002).

Database and demographic tendencies in Benin

Since all population projections are based on assumptions about future levels of fertility, mortality, and migration, a sound understanding of the previous development of these variables is essential.

Unlike some neighboring countries, Benin has never been the destination of major international migration. It is thus appropriate to take a national data basis for population projections. Demographic data are available through three censuses conducted in 1979, 1992, and 2002 by the INSAE (*Institut National de la Statistique et d'Analyse Economique*), the national office for statistics (INSAE 1993, 2003a). In 2002, the year of the last national census, Benin had 6.8 million inhabitants (INSAE 2003a; see also sect. I-3.8).

These census data give evidence on current tendencies of demographic variables, which are used as input data for population projections. Fertility has declined from 1982, with 7.10 children per woman, through 1992, with 6.1, to 2002, with 5.55 children per woman (INSAE 2003b); a decline of 1.55 children per woman over a period of 20 years. Fertility rates are higher in rural areas in North Benin compared to urban areas and the south of the country. Life expectancy has been increasing slowly from 1992 to 2002, from 54.20 to 59.20 years. It is highest for women in urban areas (64.23 years in 2002) and lowest for men in rural areas (57.33 years in 2002). The annual growth of life expectancy between the two censuses is 0.49 years (INSAE 2003b). In general, these data show a quite clear picture of the current demographic trends, which will determine the demographic development in the near future.

In the African context, most of these data have comparatively good quality, but this varies for the different variables and their spatial and administrative dimensions. Data on the number and sex of inhabitants have acceptable accuracy up to the level of the small subunits (*arrondissements*). More complex data on fertility, mortality, ethnicity or national migration are less reliable and have to be used with much caution below the regional level of the departments.

Population projections

A population projection is a "best-guess" calculation of the number of people expected to be alive at a future date, based on what is known about the current population size and the expected development of births, deaths, and migration. Population projections should not be treated as forecasts, but as provisional calculations based on certain known or assumed relationships. Therefore, when these relationships change, so should the projections which are based on them.

There are many significant demographic and social trends which need to be tracked carefully into the future. Only then can population projections be useful for a variety of purposes, most commonly as a basis for planning the future demand for infrastructure and public services (Wilson and Rees 2005). In the case of the scenario approach within IMPETUS, population projections are required as an important input for various models, for example in order to illustrate potential future deforestation rates resulting from a growing use of fuel wood or clearing during agricultural colonization processes and its impact on the hydrological cycle.

Methodological approach

In order to provide population projections at different spatial scales with the time horizon of 2025, a two-stage approach was pursued: For making projections for the whole country on the administrative level of *départements*, the demographic model DemProj was applied. Since small population size and limited data availability create methodological problems for small-area projections, a small-area projection refinement model was developed for the smaller administrative units (*communes* and *arrondissements*) which combines extrapolation of growth rates and of percentage shares of the subunits relative to the projected data on the department level.

The computer program DemProj was developed within the POLICY Project of the American development agency USAID (United States Agency for International Development), which mainly supports family planning and reproductive health programs. It is a freeware program used worldwide by professionals for making population projections for countries and regions. DemProj calculations are based on the standard cohort component projection, which subjects all cohorts to mortality and migration assumptions on an annual or five-year basis, applying fertility assumptions to women of reproductive age. It was developed by Whelpton (1936), has been formalized and refined ever since (Leslie 1948; Rogers 1966, 1986; van Imhoff 1990) and is used today for country projections by national (Shaw 2004) and international organizations (United Nations 2004).

DemProj projects the population for an entire country or region by age and sex, based on assumptions about fertility, mortality, and migration. A full set of demographic indicators can be displayed for up to 50 years into the future. The model requires the following inputs, which were provided by INSAE:

- Pop5(a,s): Population by five-year age groups (a) and sex (s) in the base year
- TFR(t): Total fertility rate by year
- ASFD(a,t): Distribution of fertility by age by year
- SRB(t): Sex ratio at birth by year
- LEB(s,t): Life expectancy at birth with AIDS by sex and year
- Model life table
- Migration(a,s,t): Net in-migrants by age, sex and time
- The population is projected by age and sex for ages 0 to 79 as Pop(a,s,t) = Pop(a-1,s,t-1) + [migration(a-1,s,t-1) + migration(a-1,s,t)]/2 – deaths(a,s,t-1,t)

As already pointed out, population projections are always based on assumptions about fertility, mortality, and migration. These assumptions should be carefully considered and require profound knowledge about the full range of national and international policies that impact these demographic parameters directly: policies as expressed in laws and in official statements and documents, operational policies that govern the provision of reproductive health services and family planning programs, policies affecting gender roles and the status of women as well as policies in related sectors, such as education and spatially differentiated development planning. Moreover, population projections for Benin consider national projections that include assumptions about the future course of TFRs and life expectancy, national population goals expressed in crude birth and death rates or contraceptive prevalence rates, recent trends and international experience as well as socioeconomic development trends and population program efforts. The qualitative decision-making procedure for making assumptions about future rates of fertility, mortality, and migration in Benin was mainly based on an intensive exchange with INSAE staff in several workshops. During these workshops, the assumptions based on the evaluation of policies, and the other above-mentioned parameters were discussed and compared to the ones developed from INSAE. The important advantage of this approach was the opportunity to access the knowledge of INSAE demographers, who are in regular discussions with multiple stakeholders and experts about their own assumptions for population projections.

Since population projections are always set on possibilities for the future and no one can be certain about the assumptions in the projection, it is highly recommended to produce several projections with different variants of each assumption so that the range of plausible projections can be determined. According to the scenario development within IMPETUS, three different projections were developed for the national and the department levels that reflect scenarios B1, B2, and B3 and their respective storylines (see fig. II-3.4.1). For example, the average life expectancy in the *département* Borgou was 54.1 years for men and 59.61 for women. Taking into account published national projections, national life expectancy goals and national and international policies that impact mortality, such as expansion of basic health care infrastructure in rural areas, HIV/AIDS programs, vaccination campaigns, and anti-malaria programs, the following assumptions were made: According to the "positive" Scenario B1, life expectancy increases significantly by 2025 to 62.8 years for men and 69.7 for women. This assumption reflects political stability, economic growth and a substantial improvement of living conditions. For the B2 scenario, life expectancies of 56.1 (men) and 62.8 (women) were assumed. This very slight increase, which is even below the average increase between 1992 and 2002, reflects the failure of national and international policies due to political instability and economic decline. The life expectancy assumptions for the B3 scenario were 60.2 (men) and 66.1 (women), which mirror the persistence of current trends: political stability, but fragmented economic development and a modest improvement in health care and living conditions.

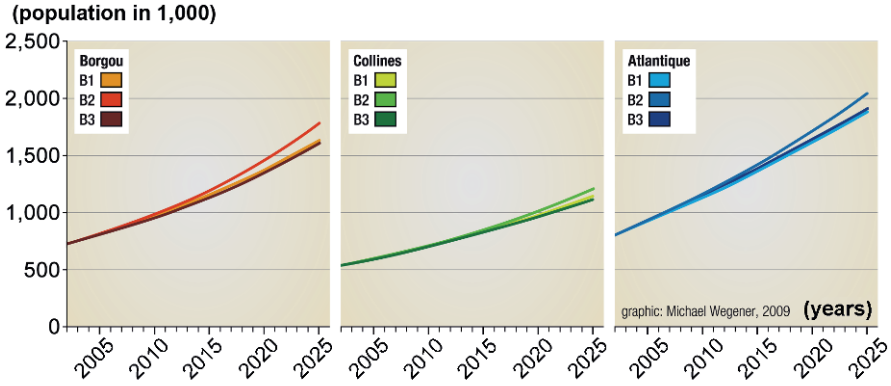

Fig. II-3.4.1: The projections of three *departements*: Borgou, Collines, and Atlantique (2002-2025).

As already stressed above, most projection techniques remain unsatisfactory for small areas due to poor data availability (Klosterman et al. 1993). Since the population projections are based on assumptions on future levels of fertility, mortality and migration, it is necessary to have sound data on past and present levels of these indicators. As this has proven to be extremely difficult in small areas within developing countries like Benin due to the lack of reliable data, the standard cohort component projections were only made on the level of the *départements*, and a small-area projection refinement model was applied in order to obtain coherent cross-scale projection data on population sizes at different administrative levels. The model combines mathematical extrapolation of past growth rates (Pittenger 1976) and of the subunits' shares relative to the *département* population (Wadembere Mugumbu 2001). The small-area populations are calculated by the mean values of the extrapolated growth of each subunit and their extrapolated relative shares in the base year applied to the projected data on the level of the department. The mean values are then converted into percentages and applied to the projected *département* data. The great advantage of this rather simple model is that on a low-quality data basis, both projected data on the higher administrative level (the subunit's share of it) and current local demographic tendencies (growth rates) are incorporated and cross-scale coherency is achieved. At the same time, it permits the display of demographic dynamics within the *départements*, which is evidenced, for example, in the case of the suburban *commune* Abomey-Calavi (fig. II-3.4.2), which will become entirely part of the Cotonou agglomeration by 2025 according to all three scenarios, with a population that will grow from 307,745 in 2002 to more than 1.1 million in 2025. Tchaourou, a rural *commune* in the *département* Borgou, will have more than doubled its population by 2025, while the population growth will be lower in the *commune* of Dassa. The charts for the three *communes* show, however, that the differences between the three estimations (B1, B2 and B3) remain small.

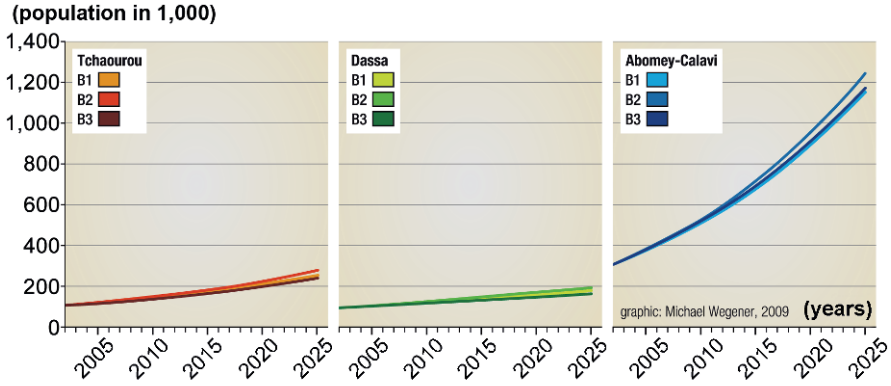

Fig. II-3.4.2: The projections of three *communes*, Tchaourou, Dassa, and Abomey-Calavi (2002-2025).

Conclusions

The projections reflecting the three scenarios B1, B2, and B3 are three plausible variants of future demographic development in Benin. The relatively short projection period of 23 years from 2002 to 2025, however, gives little opportunity for plausible antithetic demographic projections. Furthermore, the antithetic settings of fertility and mortality lead to a certain assimilation of the projected population. For the scenario B1, fertility is assumed to decline, while life expectancy is supposed to be extended. For the scenario B2, in turn, fertility is supposed to increase and life expectancy is expected to decline. The consequence is that in terms of total population, the two projections are not as different as one might expect. In 2025, the *département* Borgou, for example, will have a slightly higher population according to the projection B2 (1,779,852) than according to the variant B1, with 1,627,625 inhabitants, and the *Business as Usual* projection B3, with 1,608,618 inhabitants. The interesting differences instead concern the age structure of the population. On a longer time horizon, however, the impacts of different projection variants will become more evident.

References

Blaikie P (2008) Towards a future for political ecology that works. Geoforum 39(2):765-772
Blaikie P, Brookfield H (1987) Land Degradation and Society. Methuen, London
DESA (UN Population Division) (2001) Population, environment and development: The concise report. ST/ESA/SER.A/202. Department of Economic and Social Affairs, Population Division. United Nations Publications. New York
Harrison P, Pearce F (2000) AAAS atlas of population and environment. University of California Press, Berkely
INSAE (Institut National de la Statistique et de l'Analyse Economique) (1993) Deuxième Recensement Général de la Population et de l'Habitation. Internal governmental data set, Cotonou
INSAE (Institut National de la Statistique et de l'Analyse Economique) (2003a) Troisième Recensement Général de la Population et de l'Habitation. Internal governmental data set, Cotonou
INSAE (Institut National de la Statistique et de l'Analyse Economique) (2003b) Troisième Recensement Général de la Population et de l'Habitation. Analyse des Résultats. Internal governmental data set, published on CD-Rom. Cotonou
Jolly C (1994) Four theories of population change and the environment. Population and environment 16(1):61-90
Klosterman RE, Brail RK, Bossard EG (1993) Spreadsheet Models for Urban and Regional Analysis. Center for Urban Policy Research, New Brunswick, NJ
Leslie PH (1948) Some further notes on the use of matrices in population mathematics. Biometrika 35:213-245
Lutz W, Prskawetz A, Sanderson WC (eds) (2002) Population and environment. A supplement to Population and Development Review 28
Pittenger DB (1976) Projecting state and local populations, Ballinger, Cambridge MA
Rogers A (1966) Matrix methods of population analysis. J Am I Planners 32(1):40-44
Rogers A (1986) Parameterised multistate population dynamics and projections. J Am Stat Assoc 81:48-61
Shaw C (2004) Interim 2003-based national population projections for the United Kingdom and constituent countries. Population Trends 118:6-16.
http://www. statistics.gov.uk/downloads/theme_population/PT118_V1.pdf.
Accessed 27 July 2009
Simon D (2008) Political ecology and development: Intersections, explorations and challenges arising from the work of Piers Blaikie. Geoforum 39(2):698-707
United Nations (2004) World Population Prospects: The 2002 Revision. Volume III: Analytical Report, Executive summary. United Nations, New York.
http://www.un.org/esa/population/ publications/wpp2002/WPP2002_Vol3.htm.
Accessed 19 June 2005
van Imhoff E (1990) The exponential multidimensional demographic projection model. Math Popul Stud 2(3):171-182
Wadembere Mugumbu I (2001) Online Appendix to a Master Thesis. Geographical Information Systems. Demographic Spatial Analysis and Modelling. Master thesis, University of Science Malaysia.
http://www.hbp.usm.my/Thesis/HeritageGIS/master%5Cthesis%5C3-Small%
20area%20projection.htm
Whelpton PK (1936) An empirical method for calculating future population. J Am Stat Assoc 31:457-473
Wilson T, Rees P (2005) Recent Developments in Population Projection Methodology: A Review. Popul Space Place 11(5):337-360





4 Impacts of Global Change in Benin

4.1 Impacts of Global Change on food security in Benin

4.2 Impacts of Global Change on water resources and soil degradation in Benin

4.3 Land use and land cover modeling in Central Benin

4.4 Migration, property rights, and local water resources management in Benin

4.5 Vector-borne and water-borne diseases in Benin

II-4 Impacts of Global Change in Benin

A. H. Fink

Under the present climate conditions, physical water scarcity does not appear to be a major limiting factor for food and livelihood security in Benin. Rather, the fast demographic growth arising from high fertility rates and immigration causes a high pressure on natural resources such as soils, forests, water as well as on biodiversity, and challenges the assurance of food security and economic development. The projected climate warming and drying trend occurs in addition to these developments. In parts of the sub-humid tree savannah of Central Benin, particularly in the *Haute Vallée de l'Ouémé* (HVO), farmland expanded considerably at the expense of natural forests during the IMPETUS project period 2000–2009. In the HVO, some of the highest population growth rates in Benin in excess of 5% p.a. also occurred due to immigration mainly from the Atakora mountain area in northwest Benin. The increasing population and the prevailing extensive, labor-intensive cropping and animal husbandry systems were the major drivers of the rapid land use change that was monitored by IMPETUS in the HVO. Migrants were strongly involved in the process of agricultural colonization. In some villages in the HVO, rural migrants without secure land rights already constitute the majority of the population.

In a way, the recent described strong population and environmental changes made the HVO an ideal study region to investigate the impacts of Global Change (see chapt. I-2) on the regional and local scales. Furthermore, the low level of fertilizer use and the high mobility and adaptive capacity of the local people offers a large potential to ensure food security and economic development in the region while at the same time preserving the still relatively abundant resources. The situation in the Lower Ouémé catchment is quite different. Here scarcity of arable land and high degradation of soils in the densely populated littoral already causes difficulties in generating an adequate food supply. In a multidisciplinary approach, the disciplinary models developed, adapted, calibrated, and validated for the HVO and the entire Ouémé catchment were used in 19 problem clusters that were stratified into the five subject areas: "Food security", "Water related problems", "Land use and land cover", "Society", and "Health" (see chapt. II-1). Within the problem clusters, projections of the development of food, land, and water resources, as well as of public health aspects were performed for the coming decades using the IMPETUS socio-economic and climate scenarios (see chapt. II-3). The realization of such projections and the identification of appropriate management strategies are facilitated by implementing the models and survey results in easy-to-use Decision Support and Information Systems (DSSs and ISs, see chapt. II-2).

In section II-4.1, the recent and future adaptive potential of Benin's cropping and animal husbandry system under the projected population and Climate Change is discussed. One salient conclusion using the agro-economic model BenImpact is that subsidization of fertilizer use and promotion of measures to increase the use

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of organic matter and leguminous crops in staple food production by small-scale farmers are worthy of consideration to cope with demographic growth and a potential drying trend. This is based on the assumption that labor and land scarcity is not expected to be a limiting factor in Central Benin in the next two decades or so. Section II-4.2 discusses the impacts of the projected climate and land use changes on surface runoff, soil erosion, and renewable water resources in the Ouémé catchment using the hydrological model UHP-HRU (Universal Hydrological Model – Hydrological Response Units), the model system SWAT (Soil Water Assessment Tool), and the water management model WEAP (Water Evaluation and Planning System). One outstanding finding pertains to the fact that the number of months when the domestic, industrial, and agricultural water demand is not met in the Ouémé catchment increases from eight months per year for the period of 2002-2014 to ten months per year for the period of 2015-2025. This clearly indicates the need for improvements in access to surface and groundwater resources in this sub-humid country to avoid periods of local water stress.

Projections of land use and land cover changes using the model LUMIS (Land Use Management and Information Systems) for the HVO with the IMPETUS socio-economic scenarios are highlighted in section II-4.3. In this contribution, the consequences of the construction of a road on the conversion of forest to agricultural land are exemplified as an IMPETUS intervention scenario. The following section II-4.4 sheds light on how the coexistence of modern and customary land rights causes legal pluralism and legal uncertainty. As a consequence, land conflicts emerge, the purchase of land is problematic and property rights are unevenly distributed. An important and not well-recognized consequence has been the inhibition of agroforestry, and the plantation of cashew in particular, by traditional land owners in large parts of Central Benin because trees are seen as property symbols in large parts of West Africa. Background information on property use and water management at the commune and village level is given in the information system LISUOC (Livelihood Security in the Upper Ouémé Catchment). The last section II-4.5 is dedicated to the future spread of malaria in Benin and West Africa and the chemical, bacteriological, and microbiological contamination of drinking water in the HVO. In the latter context, the information system SIQeau (*Système d´Information Qualité de l´eau*) has been established that contains, amongst others, information on the present drinking water sources in the HVO. The future malaria prevalence is assessed using the Liverpool Malaria Model (LMM) and the IMPETUS climate scenarios. A pertinent finding is that the epidemic malaria belt in the Sahel shifts southward to southern Niger and that the malaria season in Benin might become shorter in the near future due to an overall drying trend.

II-4.1 Impacts of Global Change on food security in Benin

A. Kuhn, V. Mulindabigwi, M. Janssens, G. Steup, T. Gaiser, H. Goldbach, I. Gruber, and E. Gandonou

Abstract

Agriculture is the most important source of both income and food in Benin. Farming systems are still dominated by shifting cultivation of crops and semi-transhumant livestock husbandry. The use of modern inputs and machinery is still limited; thus land and labor are the most important factors of production, and production increases are largely achieved through the expansion of cropland areas and herd sizes. Benin's current and future potential to ensure food security is investigated by focusing on the biophysical and economic conditions facing its food supply, i.e., the production of crops and livestock products under the given resource constraints. Increasing population and land scarcity are the two most important driving factors influencing the food balance in Benin. Despite the rapid paces of both trends, no absolute land scarcity is likely to emerge in Benin in the next two decades and thus no scarcity of food. With both labor and land abundantly available, fallow has been the most important tool for soil-fertility conservation over the centuries. With land becoming scarce, soil fertility will have to be sustained by the increased use of organic matter, leguminous crops, and mineral fertilizer. The profitability of all of these 'modern' options is still precarious, preventing sufficient levels of utilization to stabilize soil fertility, land use, and food supply.

Keywords: Food security, remote sensing, farming systems, shifting cultivation, crop-yield response, agricultural policy, livestock

II-4.1.1 Introduction

The sub-humid savanna of Benin is characterized by rapid demographic growth caused by high fertility rates and immigration from both the densely populated coastal areas and the resource-scarce Sahel zone. This demographic development contributes to high pressures on natural resources such as water, soils, and biodiversity and results in high deforestation rates, decreasing soil fertility and conflicts over water and land. Future Climate Change may aggravate these problems.

Currently, agriculture is the most important source of both income and food in Benin. Ensuring food security and economic development without compromising the natural-resource base is therefore an important concern for policymakers on the national and local levels.

This section deals with Benin's current and future potential to ensure food security by focusing on the biophysical and economic conditions facing food supply, i.e., the production of crops and livestock products under the given resource constraints. More precisely, it is assumed that the potential to produce sufficient food is determined by the way productive resources such as land, labor, and time periods with sufficient rainfall are managed by farm households and social institutions. The impacts of both demographics and Climate Change on this productive potential are considered as well as ongoing and future adaptations at various decision-making levels. The section begins with an outline of the most recent adaptation processes that have been observed in response to increasing land scarcity and soil degradation in the past years, for instance the changing regional cropping patterns and practices as well as adapted fallow and fire management. Next, the question of the impact of changing climate and soil properties on yield levels is discussed extensively. In the traditional cropping systems, the productivity of grain crops in the Upper Ouémé catchment is determined by the availability of fallow land, as shown by the decreases in productivity observed with decreasing shares of fallow in the total crop rotation. In contrast, the effect of fertilizer application has had a tremendous impact on crop yields, especially with grain crops and leguminous crops. Moreover, the IMPETUS climate scenarios indicate the possibility of a substantial drying trend in the coming decades due to the degradation of vegetation and soils in West Africa.

Land-use change in Benin has occurred predominantly as an expansion of agricultural areas. To assess the sustainability of current trends, the results of long-term resource-economic simulations are presented. These are based on scenarios regarding the main driving factors of farmland expansion, such as population growth or income trends. Models for the impacts of Climate Change and demographic trends on livestock production use scenarios regarding deforestation rates and simulate the introduction of more labor-intensive (and land-saving) production modes. Conflicts over the use of land and water resources between crop farmers and herders are discussed.

This section also discusses the suitability of various adaptation strategies to cope with Climate Change and increasing land scarcity. Among these are changing crop portfolios and fallow management, restricted cultivation of marginal lands, tax supports for an increased use of mineral fertilizer, and the cultivation of temporary wetlands in inland valleys (*bas-fonds*). The soils in these inland valleys are usually more fertile and better supplied with water than the surrounding areas but require more intensive amelioration measures to be brought into cultivation.

II-4.1.2 Adaptation of farming systems in Benin

Adaptation of cropping systems

Benin has a multitude of farming systems varying in time and space according to local climate, dominant soil types, and land availability. The importance of the different crops or cropping mixes is determined by their roles in ensuring household food security and/or generating agricultural incomes (Mulindabigwi 2006). In southern Benin, farming systems are dominated by maize, oil palms, and irrigated horticulture. Yam, sorghum, groundnut, cotton, and cashew trees are particularly produced in the center of the country, but rice is also becoming an important crop in the inland valleys, which have rarely been used agriculturally until recent times. Sorghum, millet, groundnut, and cotton are found in the north (van den Akker 2000). In this region, rice and potatoes are irrigated in the Niger River basin. Whereas agricultural production systems are dominated by fallow rotation in the south and north, the farming systems in the center of Benin are still classified as shifting cultivation.

The adaptation of farming systems in Benin is mainly determined by demographic (scarcity of land), economic (transformation and marketing of agricultural production), and environmental (land degradation and rain variability) factors. It is decided by national policies in agriculture and/or by individual initiatives of the farmers. During the Marxist period in Benin (1972-1990), the main policy objective was to ensure food security. This policy was especially characterized by irrigated rice cropping, plantations of cashew trees, promotion of storage facilities in the villages, and processing facilities for raw products (e.g., tomatoes in Natitingou, cashew nuts in Parakou, etc.). Although this political commitment could not be sustained during the following years, it encouraged farmers to introduce new crops into their farming systems (rice, cashew trees, and maize), particularly in the center of Benin. While the intensification of cotton production has always been supported by the government, the production of food crops and cashew nuts has mainly been realized in extensive farming systems where yields strongly depend on the duration of the fallow. The difficulties of farmers in obtaining access to agricultural inputs (improved seeds, mineral fertilizers, and agrochemicals) and putting them to proper use has contributed enormously to the persistence of extensive production modes such as shifting cultivation. A number of farmers who understood the advantages of mineral fertilizers, particularly for maize production, have resorted to cotton production to get access to subsidized mineral fertilizers on the basis of commodity credit. Until now, it has been economically rational for farmers to divert fertilizer that was officially distributed for cotton production to some extent for the production of maize and other food commodities (Mulindabigwi 2006).

However, since the market liberalization of mineral fertilizers in 2006 and the implementation of development projects for food crops such as cassava and rice, farmers have started to use these agricultural inputs without passing them through

cotton production. One of the consequences has been the intensification and expansion of maize- and rice cultivation areas at the expense of cotton. The respective cultivated areas of maize, rice, cassava, and cashew trees have been continuously increasing since 2006. Depending on different socio-economic and technical factors, the importance of these crops is likely to be maintained even in the case of Climate Change negatively affecting their yields. Increased processing of cassava to higher-value products, rising demand from neighboring countries (especially Nigeria), and only modest demands on soil fertility are factors which contribute to the increasing importance of cassava in the farming systems of Benin. The fact that maize can substitute for yams in the food basket during the 'lean period' from March to July (center of Benin) as well as its easy marketing encourages farmers to intensify maize cropping. The opening of three new processing plants for cashew nuts in the center of Benin (Tchaourou: 1,500 t/year current capacity; Banté: 5,000 t/year; and Savalou: 5,000 t/year) will accelerate the expansion of cashew plantations in areas with lower population densities. The current introduction of irrigated potatoes in inland valleys (*bas-fonds*) from November to February offers farmers further opportunities to ensure their food security for the 'lean period" and to increase their agricultural income. Although yam is presented as a crop whose yields will not be affected by the climatic changes (Paeth et al. 2008), its importance will decrease with the disappearance of the long-term fallows.

Changes in fallow management

Demographic expansion and migratory movements have changed conditions for cropping substantially, mostly during the last five decades. The management of idle or fallow land has changed even more dramatically. What was formerly the major source of soil-fertility restoration has been gradually impoverished by both shorter fallowing periods and by excessive bush fires. The severity of the problem follows the demographic north-south gradient. Hence, soil fertility in the Middle Ouémé and the Lower Ouémé, with their sandy soils, has deteriorated, whereas the less populated Upper Ouémé, which also enjoys better soils and only one cropping season per year, remains less affected. Expansion of agricultural areas north of Parakou will continue in the future, particularly when combined with appropriate animal husbandry, including animal traction. South of Parakou the situation is likely to degrade most critically in the Middle Ouémé. Due to its higher population density, the Lower Ouémé is expected to offer a better buffer against further land degradation; improvements are already noticeable in the substantial decrease in bush fires. Peri-urban agriculture in the Lower Ouémé will continue its exponential progress to the extent that inputs and marketing facilities are encouraged.

Due to climatic and demographic differences, Benin hosts three different types of production systems according to the classification scheme of Ruthenberg (1980): shifting cultivation, bush-fallow systems, and systems with permanent production.

In the south, the production systems tend to be permanent due to the predominance of marketable crops and the high population density. In the center of the country, where the demographic pressure is still low and climatic conditions are favorable for agriculture, the production systems are generally based on shifting cultivation. Towards the north, where population density is low but the cultivated area per inhabitant is higher than in the rest of the country, the fallow systems dominate. Mulindabigwi (2006) observed a co-existence of the three production systems in the center of Benin. Generally, in the villages where population density reached 40 to 50 inhabitants per square kilometer, a band of permanent production without fallow was found around the settlements, followed by fallow systems and, in the most remote distances, fields within a shifting cultivation system. After Mulindabigwi (2006), the farmers distinguished four types of fallow:

- Seasonal fallows (6 to 12 months): These are fallows of several months, in particular in the regions with unimodal rainfall pattern. After the harvest the field stays uncultivated for several months, waiting for the next cropping season. The biomass production of these fallows depends mainly on the harvesting date of the crops. If the harvest takes place in July to August the spontaneous vegetation receives enough rain to produce a relatively large amount of biomass (2-3 t ha^{-1}). The dominant plants in these fallows are leguminous species such as *Tephrosia* ssp.
- Short-term fallow (1-2 years): This type of fallow is often due to shortage of manpower. In general, all crops, except yam, can be planted first in the rotation after this kind of fallow.
- Medium-term fallow (3-6 years): This is a planned fallow, dominated by grasses and small bushes. The soil is compacted, with only low humus accumulation, and the roots of fallow vegetation are deeper and more difficult to remove. Usually yam is the first crop after this type of fallow, occasionally cotton.
- Long-term fallow (more than 6 years): According to the FAO classification (FAO 1991), this kind of fallow is considered abandoned land and is therefore excluded from the category 'cropland'. It can be found in villages which have still-sufficient land reserves. With respect to litter fall it is almost comparable to the tree savanna. The soil is darker and more friable. The roots of the plants are less deep and thus more easily removed. As in the case of the medium-term fallow, the first cop in the rotation is yam.

With the steady increase of the importance of cashew nuts, the indigenous farmers in the villages with sufficient land in the center of Benin do not leave their fields under spontaneous fallow. They instead plant cashew trees by direct seeding together with yam at the beginning of the crop rotation and then allow the trees to grow together with the annual food crops until they reach an age of 4 to 5 years (*Taungya* system). After 4 to 5 years, when the field would normally be left as fallow, the cashew trees occupy the land as a tree plantation. In the villages with strong demographic pressures, cashew is generally intercropped with other

crops even after the establishment phase. However, such plantations are still scarce and occupy only 3% of the total cashew area in Benin (INRAB 2000). Soil organic matter (SOM) is an important terrestrial pool for carbon storage. Nye and Greenland (1960) reported that the soil under savanna vegetation stores more carbon than cropland soils. In the Upper Ouémé basin, this has been confirmed only for one pristine dense forest, whereas a site with tree savanna and long-term fallow had carbon stocks similar to those found in the cropland areas (Mulindabigwi 2006). This is explained by the frequent accidental or purposeful burning of the biomass in the savanna and fallow lands (Dale 1992).

The productive potential of *bas-fonds*

The rapidly growing population in sub-Saharan Africa necessitates an increase of food production. Inland valleys offer extensive, relatively unexploited potential for agricultural production due to their higher water availability, lower soil fragility, and higher fertility compared to the upland areas. Due to high population growth and shortage of available cultivable land, the exploitation of inland valleys will necessarily become more important to this region's future. To evaluate the agro-potential of the inland valleys of the region, a detailed field survey of the physical and socio-economic properties of these inland valleys was carried out in the communes of the Upper Ouémé catchment. This inventory was part of a multi-level analysis using field surveys, GIS, remote sensing, and an interdisciplinary modeling approach to evaluate the agro-potential of inland-valleys. The results were implemented in the BenIVIS information system and are available for decision makers in Benin.

The field survey was carried out in cooperation with the *Cellule bas-fond*, the local authority for inland-valley management in Benin. The aim of the survey was to localize the inland valleys of the communes situated in the upper Ouémé catchment and to determine their physical and socio-economic properties. While the communes N'Dali, Djougou, Parakou, Bassila, and Tchaourou were surveyed completely, only the parts located within the Upper Ouémé catchment were taken into account for the communes of Copargo, Sinende, and Bembéréké. The subject inland valleys were identified by the staff of *Cellule bas-fond* through personal interviews with local authorities (*chef de village or délégué*) in each village of the target region. With the assistance of local farmers, the extent of each inland valley was mapped using GPS. For each inland valley, a detailed questionnaire was completed to determine aspects of geomorphology, soils, hydrology, ethnic affiliation of the farmer, exploitation of the inland valleys, management structures, selling of products on the markets, etc.

During this survey, 817 inland valleys were located in the target region with a total surface of 5,563 ha. Figure II-4.1.2 shows the mapped inland-valleys. 536 of the surveyed inland-valleys were already under use, but often only a small part of the inland-valley was cultivated. Figure II-4.1.1 shows the percentages of cultivated and uncultivated inland-valley areas per commune for the rainy and dry seasons.

The exploitation rates were low, especially in the loosely populated communes in the south of the Upper Ouémé catchment (Bassila and Tchaourou). In communes with higher population densities and high degrees of soil degradation, such as Parakou, Copargo, and Djougou, the exploitation rates were already above 60% of the potential available inland-valley surface. The main crops were rice (62%), yam (17%), and maize (6%). In the dry season the cultivated area remained below 20%.

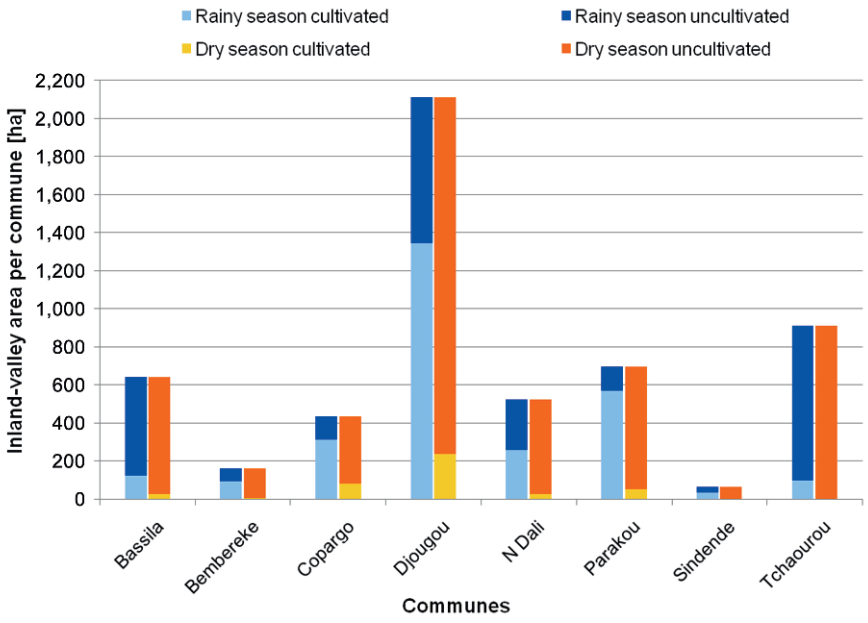


Fig. II-4.1.1: Cultivated and uncultivated surveyed inland-valley area by season and commune.

Conclusions

It appears that the changes in the farming systems of Benin have largely been driven by population growth and the need to earn monetary income. Population growth reduces the land reserves required for the traditional bush-fallow and shifting-cultivation systems. As long as food is abundantly produced, fallow is replaced by cash crops such as cotton or cashew nuts. However, these developments take place under several constraints, the relaxation of which should be in the focus of Benin's food and agricultural policy. First, farmers' access to inputs, particularly fertilizer, is constrained by an insufficient private marketing system and a lack of micro-credit for farmers. This keeps crop yields at low levels and induces farmers to use more land for the same output than in higher-productivity farming systems elsewhere in the tropics. Moreover, many crops produced cannot be marketed in larger volumes due to missing output marketing channels and the general problems in Africa with establishing and

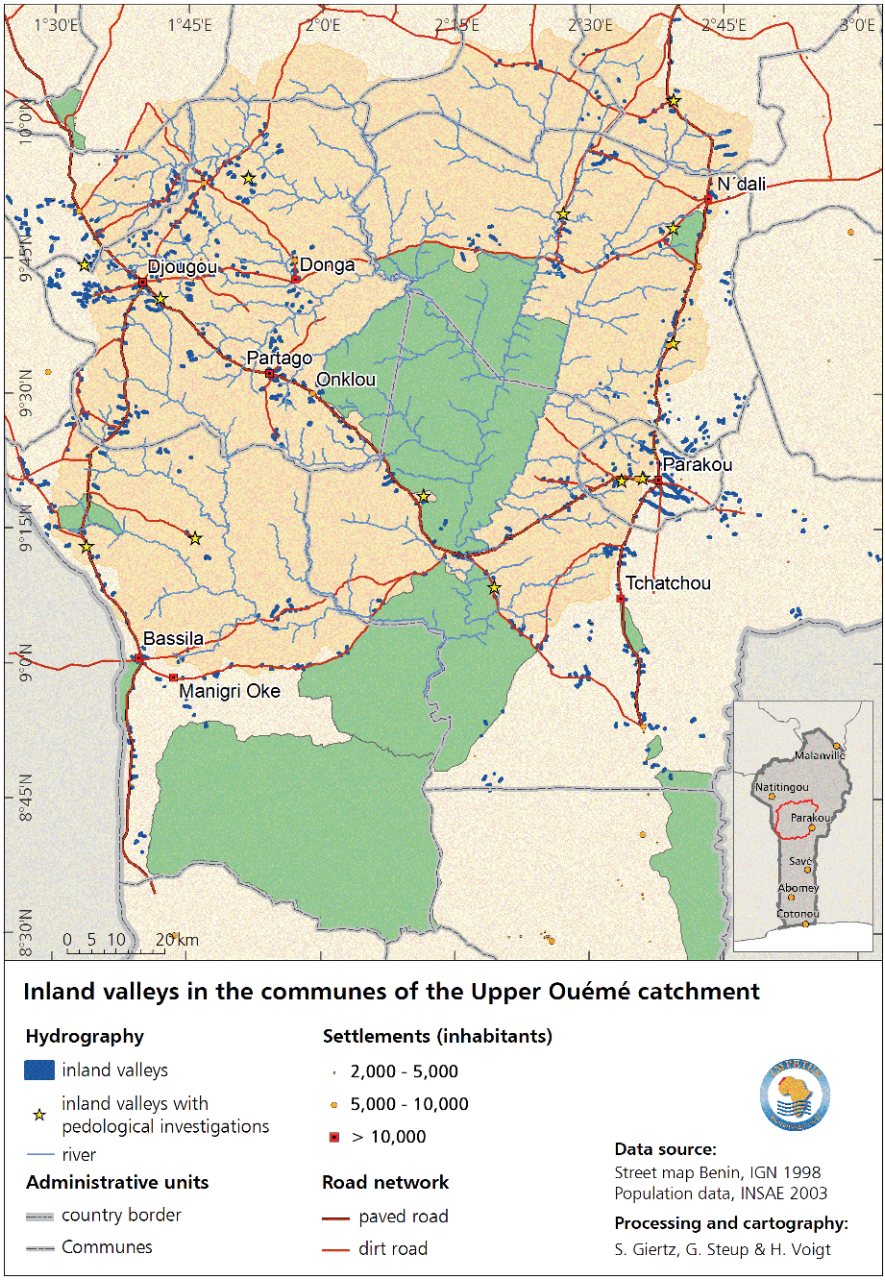


Fig. II-4.1.2: Surveyed inland valleys in the communes of the Upper Ouémé catchment.

running private businesses without excessive bureaucratic intervention. In the case of food production, the processing of raw materials is still in its infancy, in contrast to, e.g., the cotton or the oil-palm industry. An adaptation to population growth or Climate Change, while maintaining food security, cannot be successfully achieved by changes in farming systems alone but will additionally require growth and diversification of the entire rural economy. The productivity potential of cropping in Benin as a contribution to higher food security is discussed in the next section.

II-4.1.3 Crop productivity in the Ouémé catchment as affected by changes in climatic and management conditions

Crop productivity in traditional cropping systems

The high pressure on the natural resources in Benin results in high deforestation rates, a loss of soil fertility, and conflicts for water and land. However, the traditional farming systems are characterized by capital-scarce, low-input agriculture. As they result in soil degradation, along with the poor knowledge of and lack of access to modern technologies, this has lowered agricultural productivity. Soil-fertility restoration relies almost entirely on the capacity of the fallow period to replenish the nutrient stocks in the soil. Fertilizer use is restricted to areas with intensive cotton production. The mean input of mineral nitrogen, the most limiting nutrient, into cropland in Benin was about 9.23 kg ha^{-1} a^{-1} in 2002 (FAOSTAT Online Database) compared to 60 kg ha^{-1} a^{-1} in 2000/01 in Europe (EFMA 2008).

Hence, present productivity depends on the quality of the fallow vegetation and on the duration of the fallow period. In the central part of Benin, tree savanna with an appreciable number of leguminous tree and shrub species dominates the fallow vegetation, whereas in the more densely populated south of the country, grass-fallow systems are replacing tree and shrub savanna. For the Upper Ouémé basin, which is a still sparsely populated region with a proportion of about 14% cropland, simulations with the EPIC ('Environmental Policy Integrated Climate'; Williams 1995) agro-ecosystem models have been carried out on 2,556 spatial response units (for details refer to Gaiser et al. 2009, personal communication). Figure II-4.1.3 shows the effects of legume-based fallow systems and of long-grass fallows on the maize-yield level. The decrease over time of crop yield is lower in the legume-based fallow systems and can be maintained at high levels when an appropriate fallow duration is implemented. In addition, fallow duration plays a major role in soil-fertility conservation. The fallow period is related to the area of land available for a farmer and can be expressed as a fallow-cropland ratio, or R-value (Ruthenberg 1980).[1] In the departments of Donga and Borgou, Mulindabigwi (2006)

[1] The R value of Ruthenberg (1980) is the fraction of time (or land area) used for annual food crops as part of the total cropping cycle (area).

found R-values of around 0.47, corresponding to an average fallow-cropland ratio of 0.85. The results showed that, under traditional fallow systems, the maize-yield level changes over time (see fig. II-4.1.3; fig. II-4.1.4). The magnitude of yield decrease was highest without fallow (14% over 10 years) and was lowest in systems which included legume-based fallows with a fallow-cropland ratio of at least 5 (0.6% over 10 years).

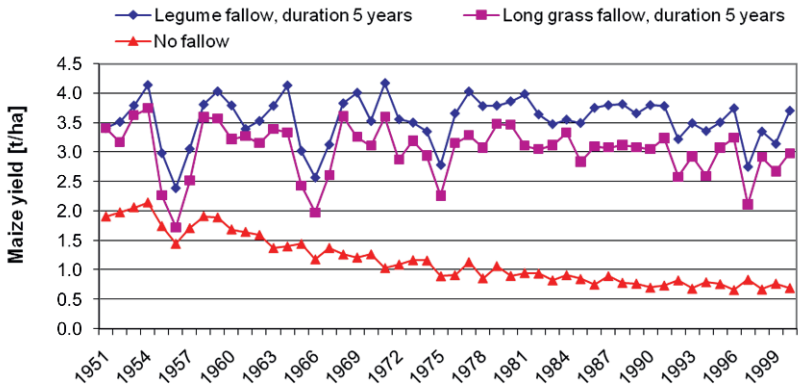


Fig. II-4.1.3: Temporal change of maize yield in relation to the fallow vegetation and equal fallow duration (50 years simulation period with 10 years of preconditioning)[2].

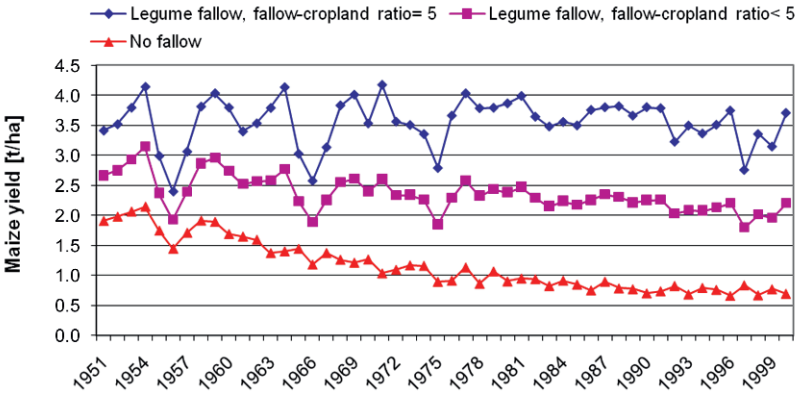
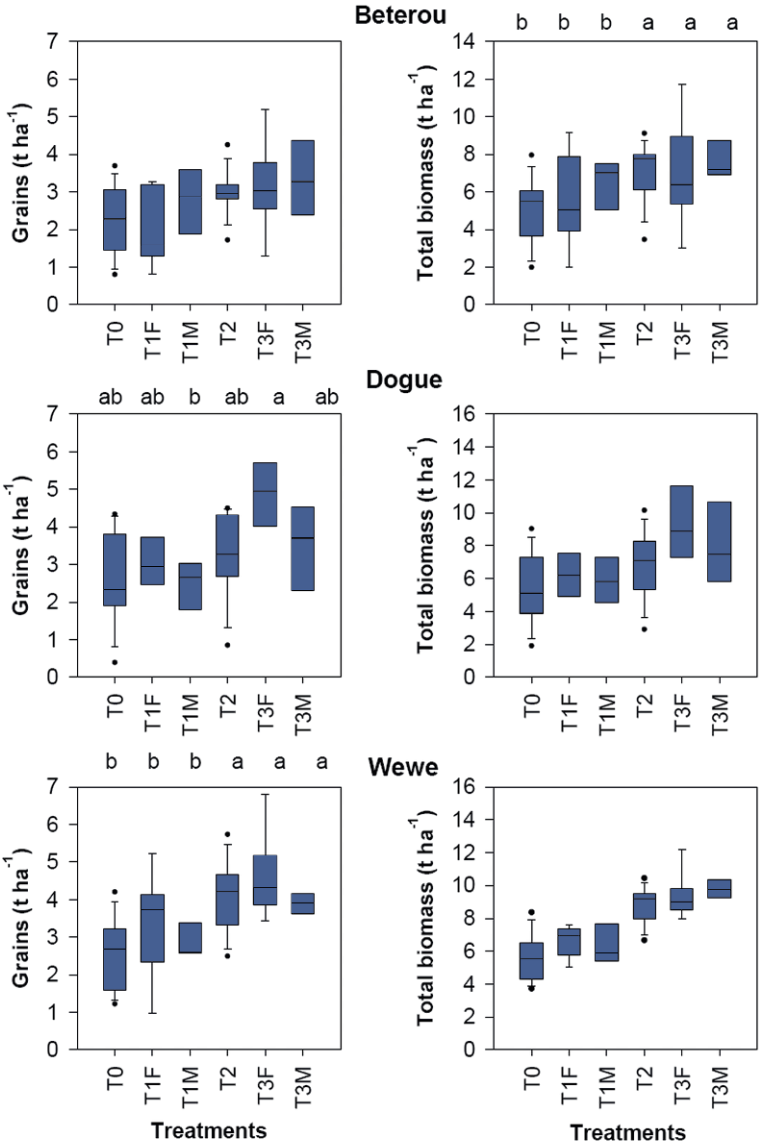


Fig. II-4.1.4: Temporal change of maize yield within legume-based fallow systems in relation to fallow duration (50-year simulation period with 10 years of preconditioning).

[2] Preconditioning is applied when only estimated initial values are available. It is a pre-run of several periods (e.g., years) which ensures that the system is in balance by characterizing the status of the system at the beginning of the true simulation period.



T0: Farmer's practice

T1F: 10 t ha^{-1} of farmyard manure of 2001

T1M: 10 t ha^{-1}of crop residues

T2: 60 N 40 P_2O_5 (2001)

T3F: 60 N 40 P_2O_5 + 10 t ha^{-1} farmyard manure

T3M: 60 N 40 P_2O_5 +10 t ha^{-1}of crop residues

Means with the same letter are not significantly different

Fig. II-4.1.5: Grain yields and total biomass of maize (*Zea mays*) as affected by organic and inorganic fertilizer application compared to farmers' current practice at three locations in the Upper Ouémé catchment of Benin (Source: Dagbenonbakin 2005).

With increasing population density due to much higher birth rates than mortality rates and additional migratory gains in the central part of the country, the cropland-fallow ratio will continue to decrease and other means of soil-fertility conservation must be explored. The most technically efficient method is to increase the amount of mineral fertilizer applied per hectare of cropland and to extend the proportion of cropland where mineral fertilizer is used.

Various on-station and on-farm trials comparing the crop yields of maize, yam, cotton, and peanuts witness the efficiency of moderate to high rates of combined mineral fertilizer (NPK)[3] with or without additional organic amendments (e.g., cover crops or cuttings from fallow vegetation) or nitrogenous mineral fertilizer (urea) (Cretenet 1993; Srivastava and Gaiser 2008). However, if low to moderate rates of mineral fertilizer are applied, the effect becomes more variable in space and time, in particular when combined with large amounts of organic materials. Figure II-4.1.5 shows the variance of the mean yields of maize in three different villages due to the application of different combinations of organic amendments along with moderate rates of NPK mineral fertilizer (60 kg ha^{-1} N, 40 kg ha^{-1} P_2O_5) (Dagbenonbakin 2005). This variability of yield effects is due to the heterogeneity of soil and rainfall distribution, and the variable nutrient content of the organic materials.

On all sites, mineral fertilizer alone increased crop yields compared to the control treatments; however, the increase was not always significant. With higher rates

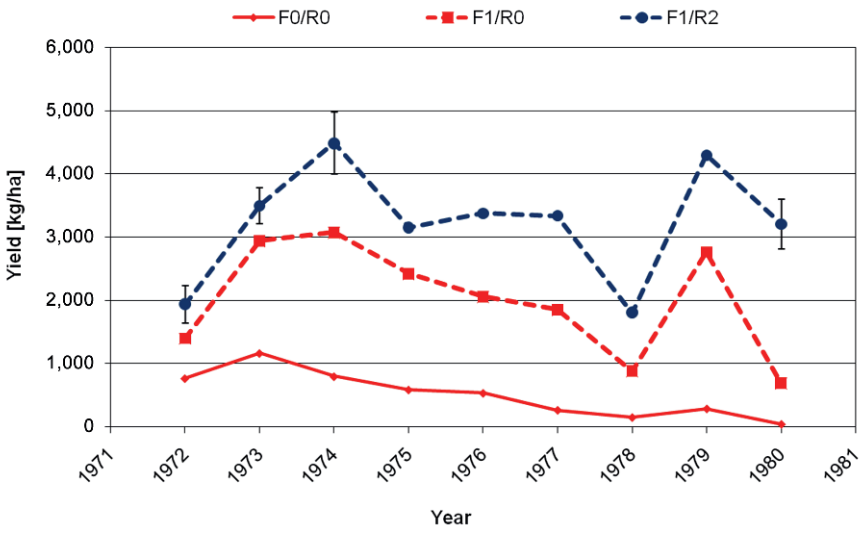


Fig. II-4.1.6: Evolution of maize yield in relation to application of mineral fertilizer (F0 = none, F1 = 116N/72P_2O_5/60K_2O kg ha^{-1} a^{-1}) and organic matter input (R0 = none, R2 = crop residues +10 t ha^{-1} fallow residues) (Error bars: LSD0.05) (Source: Cretenet 1993).

[3] NPK contains nitrogen (N), phosphorus (P), and potassium (K).

of mineral fertilizer, long-term maize and cotton yields were stabilized significantly above the control without mineral fertilizer (see fig. II-4.1.6). On highly weathered soils (e.g., acrisols or ferralsols), an adequate amount of organic fertilizer should be applied in order to avoid degradation of the physical and biological soil properties and to supply the soil with oligonutrients (Zn, Mo, etc.; see Gaiser et al. 1999). When moderate to high amounts of acidifying fertilizers are applied for several years, soil pH should be checked regularly and limestone or other buffering substances added to avoid soil acidification (Pieri 1989).

Simulations at a larger spatial and temporal scale with the spatial decision support system PEDRO (see subsect. II-2.4.1) indicated that the effect of moderate application rates of mineral fertilizers is beneficial, when applied prudently. The yield ratios for all crops simulated over the five departments in the upper and middle Ouémé basin were above one, which demonstrates the beneficial effect of the regular supply of major nutrients (see table II-4.1.1). The effect was highest with rice and lowest with cassava, which received the lowest rate of mineral fertilizer (7.5 kg N/5.5 kg P_2O_5/11.5 kg K_2O ha^{-1} a^{-1}) in the simulations. The yield ratios increased over time, mainly because of the yield decrease of crops cultivated without fertilizer.

Table II-4.1.1: Evolution of simulated yield ratios[1] of six major crops in Benin in a climate scenario from 2000 to 2025.

	2005	2010	2015	2020	2025	Mean
Maize	1.46	1.49	1.73	1.75	2.08	1.70
Rice	1.56	1.95	2.37	2.91	3.55	2.47
Cassava	1.06	1.04	1.12	1.07	1.17	1.09
Cotton	1.34	1.39	1.76	1.85	2.12	1.69
Peanuts	1.22	1.18	1.30	1.41	1.52	1.33
Sorghum	1.11	1.10	1.20	1.20	1.35	1.19

[1] Yield ratio = crop yield with fertilizer/crop yield without fertilizer

Effects of Climate Change on crop productivity

This deteriorating effect on nutrient availability of the reduction in the fallow-cropland ratio may be aggravated by the expected Climatic Changes. Figure II-4.1.7 shows the mean annual precipitation in the Upper Ouémé basin averaged over the last four decades (1960-2000) compared to the precipitation derived from the dynamic downscaling of the climate scenarios A1B and B1 using the REMO model (see subsect. II-3.2.5).

The mean annual precipitation over the four decades in the past was around 1,100 mm, although high inter-annual variability occurred within these decades.

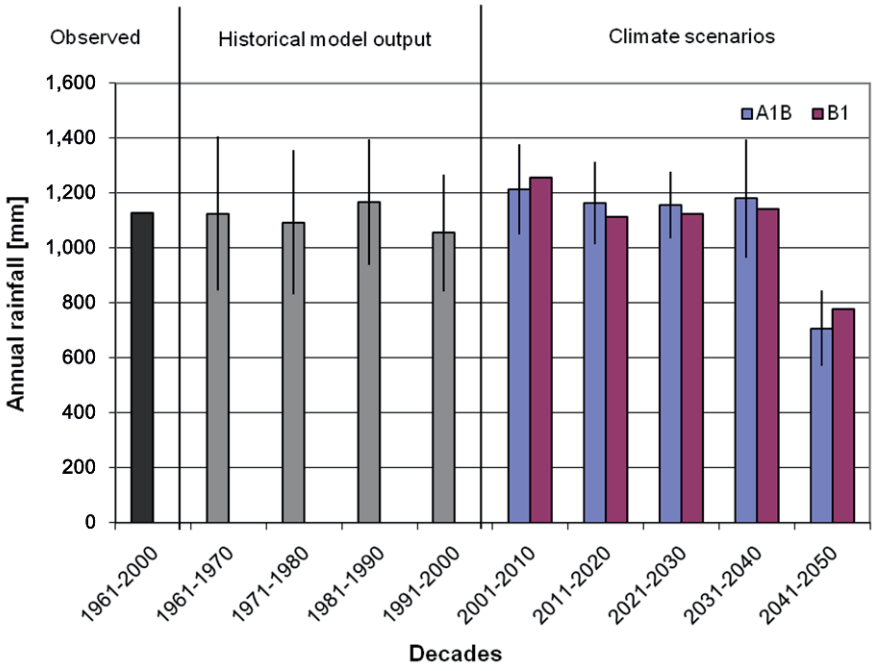


Fig. II-4.1.7: Mean annual precipitation in the Upper Ouémé basin in ten-year periods in the past and in the future according to a dynamic downscaling of output from the GCM ECHAM5 model for climate scenarios A1B and B1. The error bars indicate the range of area-averaged precipitation as derived from the three respective REMO integrations of scenarios A1B and B1. The leftmost bar shows the observed mean annual precipitation for the period 1960-2000.

It is expected that the inter-annual variability will at least persist, but in addition it is likely that the mean annual precipitation may decrease by about 30%. In parallel, until 2050 the mean annual temperatures in the IMPETUS downscaled climate scenarios A1B and B1 are expected to increase by 8.3 and 6.4%, respectively. Note that the projected temperature increase according to the IMPETUS downscaled scenarios is augmented with respect to the IPCC 4AR due to the inclusion of vegetation degradation in the REMO model (sect. II-3.2.5). The consequences on crops with high demands for sufficient and evenly distributed rainfall such as maize will be detrimental. According to long-term simulations up to 2050, the increasing soil moisture deficit may reduce the average yield levels of maize by up to 75% in the decade 2041-2050 (see fig. II-4.1.8). In addition, the production risk is likely to increase, as expressed by the higher inter-annual variability in this decade (the larger error bars in figure II-4.1.8).

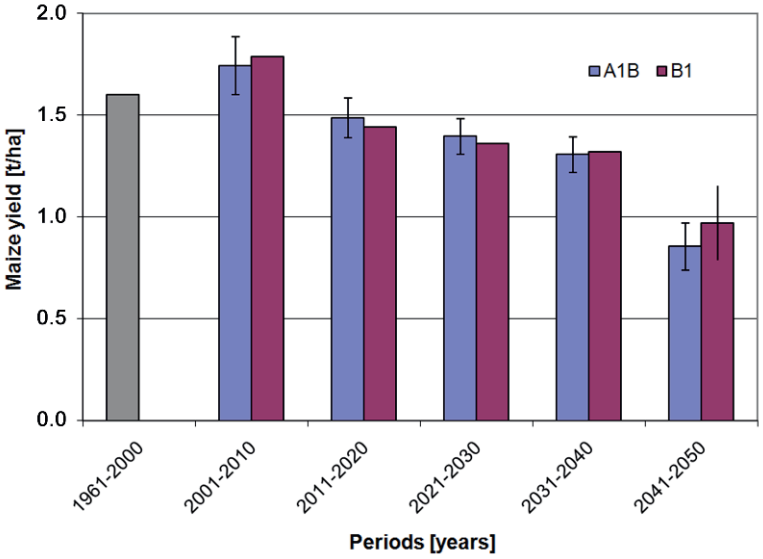


Fig. II-4.1.8: Simulated yield response of maize to changes in rainfall and temperature conditions for climate scenarios A1B and B1.

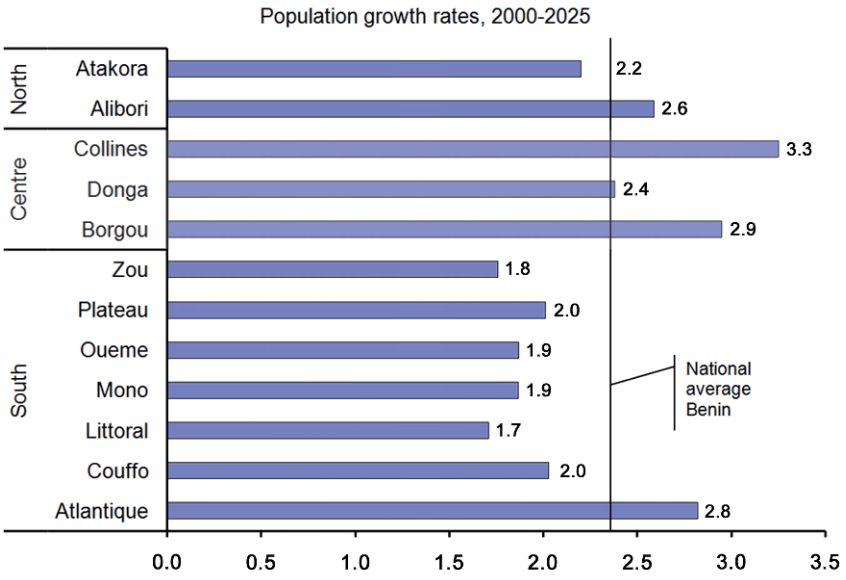


Fig. II-4.1.9: Projected regional population growth, 2000 to 2025.

II-4.1.4 Economic scenarios for food markets and land use

Land-use change in Benin has occurred predominantly as an expansion of agricultural areas. To assess the sustainability of current trends, long-term resource-economic simulations were carried out with the model BenIMPACT, which has already been described in subsection I-8.2.1. The scenarios employed were based on assumptions regarding important exogenous driving forces such as population growth or changes in non-agricultural income. Figure II-4.1.9 shows the regional distribution of population growth rates.

The regional patterns of projected population growth reveal hotspots of increase, not to a great extent in urban areas, but rather in regions which combine abundant land reserves and a supportive climate for cropping located in the center of the country. Internal migration within Benin is to a considerable extent a rural-rural migration of people from the south suffering from land scarcity, and people from the north suffering from a combination of land scarcity and unfavorable climate conditions. Rural population growth is the main driver of increased regional farmland expansion, as it increases the regional pool of farm-labor resources.

The baseline scenario of BenIMPACT assumes that agricultural land use is expanded primarily due to the lower opportunity costs for farm labor provided by high population growth. Simultaneously, the consumption of food commodities increases because of population growth and the growth of per-capita income. Income consists of two endogenous elements, farm income and income from off-

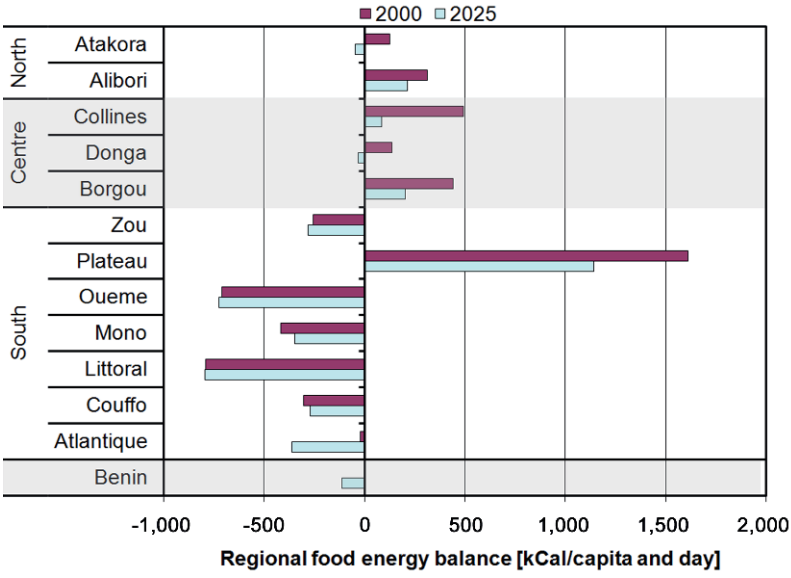


Fig. II-4.1.10: Regional food-energy balances in the BenIMPACT baseline scenario, 2000 and 2025.

farm labor, and an exogenous non-agricultural income component which is assumed to increase at one percent annually in real terms. However, it may well be that this projection on income growth may be too optimistic, so a cautious exploration of the possible future developments should also take less-optimistic growth expectations into account. This is also relevant for Benin, as the country's arable land resources are becoming more and more scarce and degraded. While repeated shortfalls in domestic supply might easily be balanced by food imports financed by the non-agricultural sectors under continuing economic growth, a future 'growth shortfall' might lead to a food gap.

Figure II-4.1.10 compares regional food-energy balances for the base year 2000 and the simulation year 2025. These 'calorie balances' are calculated as the sum of food energy per capita delivered by basic food crops produced in a region minus the amount of food energy consumed. As food consumption per capita was not expected to change significantly over the projection period, the changes were mostly driven by changes in the production of food crops. In 2000, most regions in Benin produced slight crop-energy surpluses. However, the existence of densely populated deficit regions, such as the southern communes of Cotonou, Porto-Novo, and Mono, led to an almost balanced national food energy equation of 5 kCal per capita and day (surplus). Given a continuation of current trends in population and income growth, these surpluses would significantly decrease in most regions. Although most regions would still produce food energy surpluses, by 2025 the national balance would become a deficit of 490 kCal per capita per day, which is almost one-fifth of the average individual food-energy requirement.

The projection for the expansion of cropland use is shown in the next graph (see fig. II-4.1.11). Crop areas will almost double in the central parts of Benin, i.e., the departments of Borgou, Collines, and Donga. The two northern departments of Alibori and Atakora will also see considerable increases in land use. The southern departments of Benin, however, will increase land use much less, mainly because the opportunity costs of land there will increase much more strongly due to higher land scarcity and more competition from other uses (e.g., settlements) in the south.

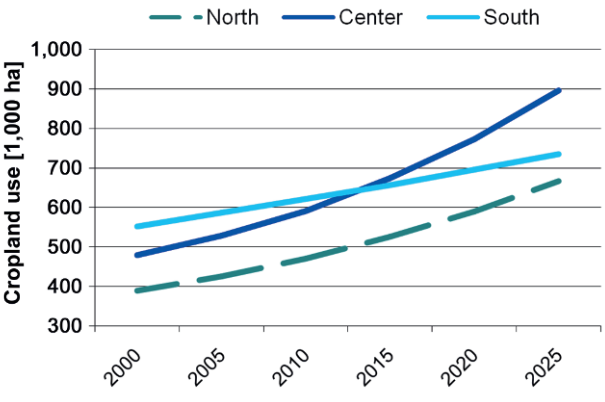


Fig. II-4.1.11: Expansion of cropland use for larger regions, 2000 to 2025.

To put the results for land use into perspective, they should be compared to the expected rural population growth, which is the main driver for crop-area expansion.

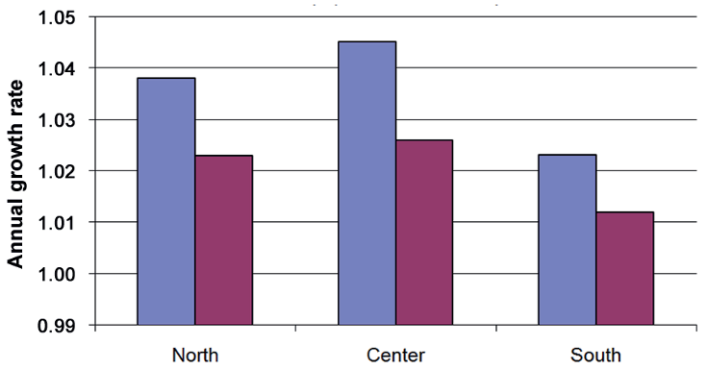


Fig. II-4.1.12: Annual growth rates of the rural population versus cropland expansion in the baseline scenario of BenIMPACT.

Figure II-4.1.12 displays the growth rates of the rural population in the three major regions of Benin compared to the simulated cropland expansion.

In all three major regions, cropped-area expansion seems to be proportional to rural population growth, but at significantly lower rates. The comparison makes it clear that, unless Benin's agriculture manages to improve its productivity, domestic production will not keep pace with both rural and total population growth. The latter is due to urbanization processes, which occur at a higher rate than rural population growth alone.

II-4.1.5 Consequences of deforestation for livestock management

In Benin, diets vary by region and season and are based on arable crops, whereas animal products are not yet very important in the daily Beninese diet. In 2003, the average annual intake of meat amounted to only 8.2 kg per capita (Toigbe 2004). These modest consumption amounts may rapidly increase if the economic development continues to grow as it has in the past years (see sect. I-3.9). A higher demand for meat will be the likely result of increasing income, as it leads to higher meat consumption per capita, and a faster-growing population. So far, higher demand has been met by increases in animal numbers, augmented by imports (Gruber 2008). Local experts assume that imports will not be able to satisfy the foreseeable additional demand in the future. Over time, the most likely response will be higher meat production per animal.

The currently dominant mode of extensive animal husbandry depends on land area not used for arable crops and on the right of access to forests and fallow areas. Pollarded trees are an essential part of the forage for ruminants during the dry season. Additionally, forests contribute to the production of fuel wood, food, and soil conservation and form an important part of a controlled water cycle. An

increase in population not only raises the demand for meat but also increases the demand for crop products. The latter aspect leads to an expansion of farmland and thus a reduction in available grazing areas for extensive livestock production.

To overcome future scarcities resulting from the extensive production mode, it is envisaged that semi-intensive production will emerge when increasing demand for animal products concurrently increases prices. Higher output prices for livestock products could be an incentive to produce more intensively with higher labor input while saving land. Thus, in the BenIMPACT model, semi-intensive animal production is an additional production option for livestock keepers if land for pasture is scarce. Here this bio-economic model was used to quantitatively analyze the consequences of deforestation on livestock management.

The analysis began by assessing the impact of reduced deforestation on livestock numbers, an important indicator for the development of this sector. Livestock numbers per region were aggregated through the Tropical Livestock Unit (TLU), which corresponds to 250 kg live weight. Along with the simulation of livestock numbers using the current yearly deforestation rates of 2.2% (the status-quo scenario), figure II-4.1.13 presents the situation where a yearly deforestation of just 0.1% was assumed (optimistic-conservation scenario). This low deforestation rate should be considered to be the lower limit. When a low deforestation was assumed livestock production grows in the northern region. However, only an extensive animal husbandry was simulated in the northern region, whereas the develop-

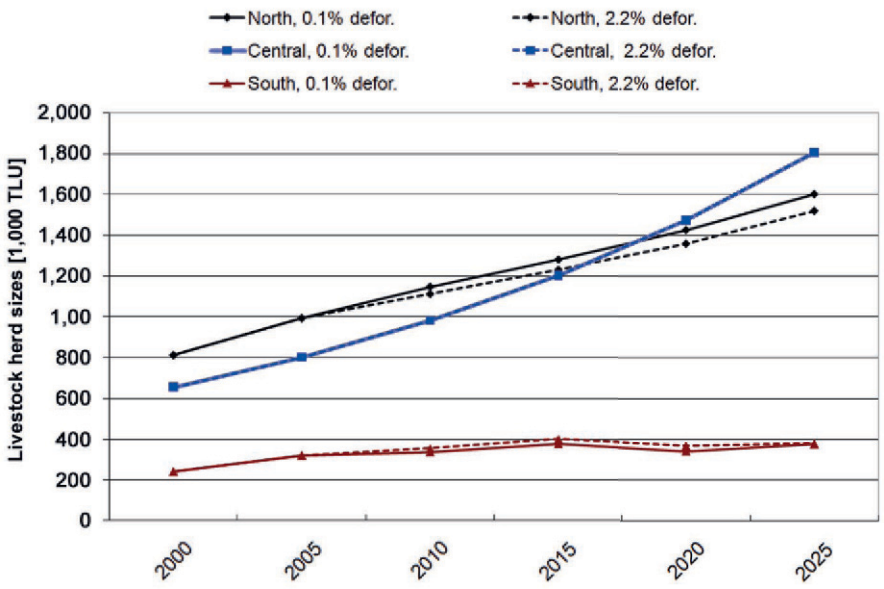


Fig. II-4.1.13: Simulation of livestock inventories until 2025 considering different deforestation rates (2.2% deforestation p.a. and 0.1% deforestation per annum (Source: Gruber 2008).

ment of activity levels appears to be reversed in the south. Here the levels in the scenario with conservation measures were smaller than in the status-quo scenario. The generally higher production of animal products in the northern region reduced the semi-intensive production in the south due to marginally lower prices.

The activity levels in the central region were nearly unaffected by the different deforestation rates. This should not lead to the assumption that the central region can easily ecologically compensate for the losses in forest area. This model result simply indicates that the fodder availability is probably sufficient in the long term as long as access to all pasture areas is guaranteed. Although the semi-intensive production becomes economically more interesting if fewer forests are available for extensive ruminant keeping, the increasing semi-intensive production cannot compensate for the reduction in extensive ruminants, which is also reflected in the production of meat.

The results so far were modeled using shadow prices of land, but without considering land rents as long as land was easily available. However, as (small) land rents have a strong influence on semi-intensive ruminant keeping, the outcome of the simulation altered stocks of ruminants more if land rents were considered.

Both aspects, deforestation and land rents, have an effect on the number of ruminants as well as the number of monogastric animals according to the simulation runs: deforestation leads to a reduction of extensively kept ruminants in the northern and central regions. A further reduction of semi-intensively kept ruminants occurred in the south if land rents were introduced as production became less profitable. Therefore, the relevance of the contribution of monogastric animals to the production of animal products varies according to the assumed deforestation rates and opportunity costs of land. In the base year 2002 the non-ruminants contributed 30.4%of meat production. By 2025, non-ruminants provided 28.5% of meat production without semi-intensive production. In the scenario with high deforestation rates and without land rent, the contribution of non-ruminant meat reached 30.7% and 31.3% with a land rent of 1,000 FCFA per ha. When the deforestation rate was set to 1.1% (a realistic conservation scenario), the meat production of monogastric animals amounted to 30.5% without land rent or to 31.0% with a land rent of 1,000 FCFA per ha. However, the shift in the composition of meat production was not significant enough in any scenario to be considered a substantial change.

II-4.1.6. Increased use of mineral fertilizer: Higher food security?

The very low increase in the productivity of staple crops largely explains the increased dependence of African countries on food imports. The use of mineral fertilizer may dramatically improve the food balance of many countries and result in lower food prices, higher food supply and consumption, improved food security, and better nutritional status. Moreover, when applied with care, fertilizer use may save land, water, and labor and thus relieve the pressure on natural resources from

growing populations. Current fertilizer policies in Benin, however, are biased in favor of the cotton sector, while all other fertilizer use is subject to import duties and value-added taxes. Scenario simulations show that tax exemptions for fertilizer sales may help to improve the nutritional situation in Benin and curb the increasing reliance on food imports.

Fertilizer policy in Benin

Benin's agriculture is dominated by the production of staple crops by subsistence farms and the production of cotton lint as a major source of export revenues. These two sectors receive different levels of attention by agricultural policy, which becomes particularly apparent by the fact that programs to promote the use of fertilizer have been closely linked to cotton production (Adégbidi et al. 2000). As cotton accounts for roughly 90% of Benin's export earnings, government interventions in that sector have been aimed at ensuring a constant and sufficient supply of seed cotton to the local cotton-processing plants. The most important tool for stabilizing the cotton supply is the control of fertilizer supply to individual farmers on the basis of a commodity-credit scheme and at pan-territorial prices which involve tax exemptions and transport subsidies in most years. The amount of fertilizer offered to farmers at lower tax rates depends on the regional cotton area. Economically, this policy can be classified as a fertilizer quota which is adapted annually to the expected expansion of regional cotton areas. The price for fertilizer sold within this quota system (the 'in-quota price') is kept uniform across regions (pan-territorial) and also across the different types of fertilizers, ignoring differences in marketing costs and quality. This resulted in pan-territorial prices of CFAF 95 to CFAF 235 per kilogram over the period 1992-2007, with a doubling of the price in 1994 after the devaluation of the FCFA. The pan-territorial 'in-quota' price is implicitly subsidized by its exemption from import duties and VAT, and, when deemed necessary, directly subsidized by import credit, transport to the destination, and distribution among farmers. As to the magnitude of tax exemptions granted to fertilizer sold within the cotton system, Adégbidi et al. (2000) estimated that import duties applied to fertilizers were around 29% until 2000. For comparison, the VAT applied in Benin is 18%.

In contrast to prices, the quantities of fertilizers used by farmers are much more difficult to monitor. According to official statistics, national consumption reached a peak at about 95,000 tons in 1999. The IFDC (International Centre for Soil Fertility and Agricultural Development) claims that the cotton sector represents 96% of the fertilizer consumption in Benin (IFDC 2005). As a consequence of the fertilizer-quota system, it is indeed plausible that national and regional consumption of fertilizers is closely associated with the importance of cotton production. There appears to be a strong link between officially recorded fertilizer use and cotton-cultivation area, as displayed in figure II-4.1.14.

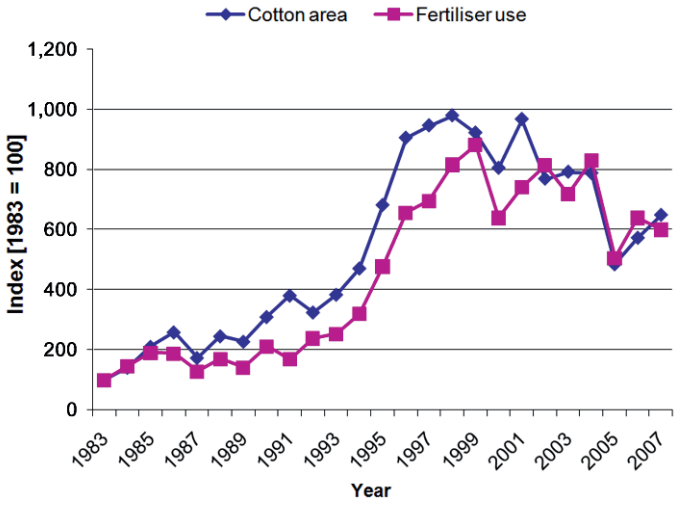


Fig. II-4.1.14: Index of total cotton-cultivation area and total fertilizer use in Benin, 1983-2007 (1983=100) (Sources: Adégbidi et al. 2000, for 1983-1999, Honfoga 2006, CSPR/AIC-infos 2008).

In addition to this finding on the national level, figure II-4.1.15 reveals a close association between the share of cotton in total cropland and the use of fertilizers per hectare, using commune-level data for the period 2001-2004.

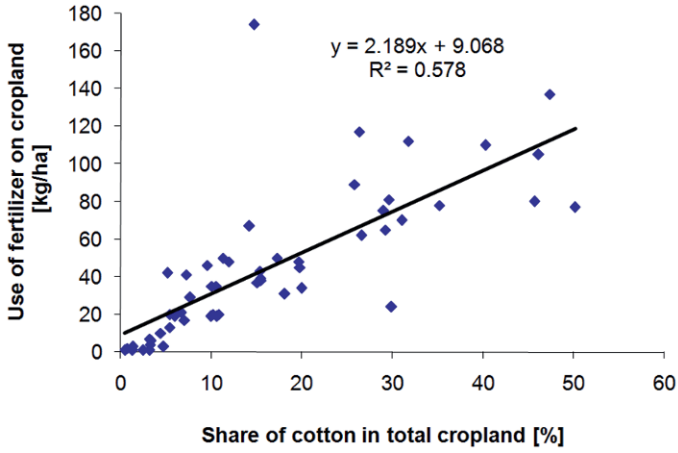


Fig. II-4.1.15: The relation between the share of cotton in the regional crop rotation and regional use of fertilizer per hectare (Sources: Matthess et al. 2005; our calculations based on CSPR 2008).

It is, however, likely that farmers allocate part of the fertilizer provided for cotton production to other crops depending on their profitability relative to cotton. Surveys by Minot et al. (2000) and Adégbidi et al. (2000) indicated that maize, rice, and vegetables are the food crops that receive the largest share of fertilizers besides cotton. To augment the fertilization of non-cotton crops, farmers may purchase additional fertilizer outside the cotton system, particularly in regions with small cotton areas and correspondingly small fertilizer quotas. To improve the productivity of staple crops in Benin, one option could be to lower the costs of fertilizer on this 'free market' in a way similar to that for cotton producers and regions.

Endogenizing the use of fertilizer in BenIMPACT

To simulate the impact of changes in fertilizer policy on cropping patterns and commodity markets in Benin, the use of fertilizer had to be made into a decision variable. The economic rationale of farmers to use fertilizer depends on the crops' yield response to fertilizer, which called for the implementation of a yield-response function. This was achieved using quadratic approximations of the results delivered by the EPIC simulations described above. The quadratic function was chosen as:

$$y_{sim} / y_{bas} = \beta_1 + \beta_2 x + \beta_3 x^2 \qquad \textbf{(eq. II-4.1.1)}$$

with y denoting base (without N-application) and simulated crop yields, and x the application of N per hectare in tons. The parameters of the quadratic yield functions are presented in table II-4.1.2. The constants β were all estimated at close to 1 and are thus not reported.

The final step necessary to implement the endogenous yield functions into BenIMPACT was to calibrate the crop-specific use of fertilizer for the base year. This was achieved by simultaneously choosing profit-maximizing levels of N applicati-

Table II-4.1.2: Coefficients of the quadratic crop-yield functions for N-application.

	Quadratic coefficient (β_3)	Linear coefficient (β_2)
Maize	-176.27	32.77
Cotton	-95.17	31.66
Cassava	-195.58	35.20
Rice	-171.30	24.72
Peanuts	-125.90	21.76
Sorghum	-63.70	9.79
Yams	-612.33	44.68

on x_i and 'base yields' y_i^{bas} (yields that would prevail without the use of fertilizer). These levels must satisfy the first-order-condition for the use of NPK-fertilizer with an N content of c[4].

$$\overbrace{\frac{p^{cif} + p^{Q}}{c}}^{\text{marginal costs}} \geq \overbrace{2 \cdot y^{bas} \cdot \overline{p} \cdot \beta_3 \cdot x + y^{bas} \overline{p}}^{\text{marginal revenues}} \quad \perp \quad x \qquad \textbf{(eq. II-4.1.2)}$$

The inequality is interpreted such that fertilizer will be used only if marginal revenues from N application equal the marginal costs of fertilizer use. The marginal costs consist of the *cif*-price (equal to the import price) of NPK fertilizer plus a regional quota rent depending on the amount (quota) of tax-reduced fertilizer available in the regions as a result of cotton-management policy in Benin. The upper limit of the quota rent is the *cif*-price multiplied by tax rates (customs and VAT) and a marketing margin of 25%, plus transport costs to the region of destination. The regional fertilizer quotas were estimated on the basis of the linear regression function outlined above. Without the quotas of non-taxed fertilizer, application of fertilizer in Benin would be considerably lower than observed. The results of the

Table II-4.1.3: Estimated regional fertiliser quotas, use, farm-gate prices, and quota rents in the base year (2000).

	'Fertiliser quota' in metric tonnes	Fertiliser use in metric tonnes	Over-quota use in %	Farm-gate price[a] in FCFA/kg	Pan-territorial price (207) plus quota rent in FCFA/kg
Alibori	28,566	28,566	0.0	475	419
Atakora	13,327	13,327	0.0	469	418
Borgou	21,872	23,127	5.7	465	422
Donga	4,576	5,317	16.2	462	444
Collines	6,041	13,718	127.1	445	445
Atlantique	100	6,309	6,209.5	426	426
Couffo	5,198	7,028	35.2	432	432
Mono	224	2,232	896.6	427	427
Ouémé	110	2,112	1,820.1	423	423
Plateau	2,532	8,451	233.8	435	435
Zou	6,305	7,977	26.5	434	434
Benin total	88,851	118,165	33.0	452	432

[a] cif plus taxes, transport, marketing, and input credit

[4] For each crop i, index omitted in the formula. The N content c in a bundle of NPK and urea is assumed to be 25% on average.

calibration process are shown in table II-4.1.3. In some southern regions in Benin where there is almost no cotton production, quotas are very low. Consequently, farm-gate prices equal the *cif*-price plus maximum quota rent.

The results show that the tax exemption of fertilizer for cotton production lowers the farm-gate prices, particularly in the north of Benin. In Alibori, fertilizer costs would be more than 13% higher in the base year than with a quota. For all of Benin, the estimated use of fertilizer exceeds the sum of estimated regional quotas by one-third. The estimated fertilizer use above the regional quotas may not originate from 'official' imports and thus does not show up in official statistics. Its 'real' value may be either higher or lower, depending on unobserved costs and benefits that could not be included in the normative calibration procedure described. If the *cif*-price were the farm-gate price throughout Benin (i.e., if the quotas were infinitely large), the calibration procedure estimates a national fertilizer use of 224 thousand tons, even though this comparatively large result does not take into account the market repercussions of the tremendously increased supply of produce.

Scenario design

Our scenarios assume that fertilizer use in Benin is constrained by import and domestic taxes. To demonstrate the medium-term effects of tax exemptions for fertilizer – corresponding to an indirect subsidy of fertilizer use – on farm production and food markets in Benin, counterfactual simulations were carried out covering the period between the year 2000 (the base year of BenIMPACT) and 2025. The *baseline scenario* assumes that the current policy scheme will be continued throughout the simulation period, with fertilizer quotas increasing in line with re-

Table II-4.1.4: Yield trends in the scenarios (increase from 2000 levels in percent).

	Baseline for 2025			Effect of tax exemptions on fertiliser use		
Year	**2005**	**2015**	**2025**	**2005**	**2015**	**2025**
Rice	-0.1	1.0	1.1	-0.1	13.7	14.6
Cassava	3.3	9.4	14.1	3.3	19.1	22.3
Maize	-0.4	0.6	3.3	-0.4	26.5	29.2
Yams	-1.0	-1.7	-2.3	-1.0	-1.7	-2.3
Sorghum	0.2	0.5	0.6	0.2	0.4	0.6
Pulses	-0.4	-0.8	1.5	-0.4	32.4	33.4
Peanuts	-0.6	-1.1	-0.8	-0.6	18.8	19.3
Cotton	-1.0	-3.1	-4.3	-1.0	20.1	18.0

gional cotton areas. The *counterfactual scenario* envisions that the 'tax exemptions' granted to fertilizer for cotton production are made universal to all fertilizer uses. This means that from 2010 onwards fertilizer prices would be exempt from taxes and VAT. The simulated use of fertilizers to increase the crop yields is in line with the IMPETUS socio-economic scenario B1, while the baseline scenario is part of the overall IMPETUS scenario B3 (see section II-3.3).

Selected results

The description of the results starts with table II-4.1.4, comparing the development of crop yields due to the different paths of fertilizer use between the scenarios.

Under the tax-exemption scenario, yields for the majority of crops would increase substantially, by up to one-third of their level in the year 2000. The impact of those productivity gains will reduce land consumption and positively affect market balances and food consumption.

Table II-4.1.5: Crop-specific use of fertiliser (NPK) in kg/ha in the two scenarios.

	Base year 2000	Baseline scenario, 2025	Tax exemptions on fertiliser use, 2025
Maize local	0.0	1.5	27.2
Maize improved	12.2	19.2	84.6
Rice	86.2	87.0	139.6
Sorghum	0.0	0.0	0.0
Cassava	113.0	160.9	196.6
Yams	0.0	0.0	0.0
Pulses	17.1	19.8	97.3
Peanuts local	70.3	66.3	146.3
Peanuts improved	120.6	110.5	174.6
Cotton	213.9	193.4	303.8

Fertilizer use per unit of cultivation area of individual crops and in total developed quite differently in the two scenarios. Table II-4.1.5 shows national averages of fertilizer use for individual crops, while figure II-4.1.16 compares total regional use across scenarios. For the crops, increases in fertilizer use correspond to the yield increases shown above. The regional distribution of changes is interesting, as it shows that without policy change, use will not change significantly over the observed period. The baseline scenario exhibited slight decreases in the north caused by declining relative profitability of cotton production, and minor improvements in the south. National use per hectare was projected to increase by only 2.5% on

average over the entire period. General tax exemptions will increase fertilizer use substantially, particularly in southern regions where quotas of subsidized fertilizer had been small.

As price signals by increased demand will remain weak under an unchanged currency regime, closing a future food gap for Benin will require productivity gains. The scenario with tax exemptions for fertilizer showed that deficits for most products would be much smaller compared to the baseline scenario, most prominently for maize and yams, but also for rice and cassava (see table II-4.1.6).

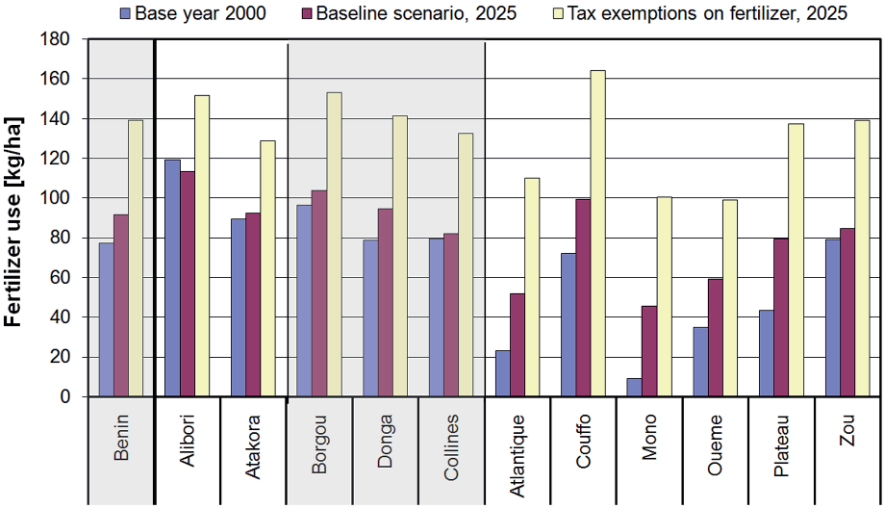


Fig. II-4.1.16: Regional use of fertilizer in 2000 (base year) and 2025 (*baseline scenario* and the *tax-exemptions scenario*).

In both scenarios national cropland use was projected to increase at a rate of about two percent annually (see table II-4.1.7), which is significantly lower than rural population growth, which was assumed to increase by more than three percent annually. As to the validity of the projected land use, the observed increase in arable land between 1999/2000 and 2004/2005 was estimated at 1.5% by Beninese official sources (regional agricultural statistics) and at 2.9% by FAO (2008). The BenIMPACT runs thus instead envisage land-use expansion lagging behind population growth, at least as long as off-farm job opportunities are sufficiently available for the members of farm households.

The simulation results suggest that tax exemption might well induce an increased use of fertilizer and thus improve agricultural productivity in Benin. Given the projected population trends, Benin will have to improve crop yields to overcome the limits of land availability and soil fertility. Thus, it is considered useful for the state budget to waive some customs and VAT revenues for the sake of an improved food supply. The value of tax exemptions was estimated at about 25 billion FCFA

Table II-4.1.6: Surplus or deficit for all regions of Benin [in 1,000 t and in percent of domestic use].

	Base year 2000		Baseline scenario, 2025		Tax exemptions, 2025	
	in 1,000 t	% of use	in 1,000 t	% of use	in 1,000 t	% of use
Rice	-150.0	-85.0	-367.0	-89.7	-351.1	-87.6
Cassava	162.7	15.4	146.8	6.7	161.0	6.9
Maize	81.2	21.1	-185.6	-20.5	-5.8	-0.6
Yams	28.0	3.1	-60.2	-3.1	-48.2	-2.5
Sorghum	-34.1	-19.5	-170.4	-40.0	-160.2	-38.2
Pulses	-6.8	-9.1	-86.6	-45.3	-44.6	-23.4
Peanuts	27.0	31.8	-25.0	-12.4	37.1	18.7
Cattle meat	0.08	0.4	-13.2	-26.2	-11.7	-23.8

Table II-4.1.7: Results for land and fertilizer use in Benin across scenarios.

	Base year 2000	Baseline scenario, 2025	Tax exemptions, 2025
Total cropland use [1,000 ha]	1,416.90	2,296.20	2,364.30
Cropland use, change to 2000 [percent]	-	62.10	66.90
Cropland use by rural population [ha/capita]	0.57	0.41	0.42
Use of NPK fertilizer [1,000 t]	118.20	196.30	361.30
NPK use, change to 2000 [percent]	-	66.20	205.80

in 2025. Assuming that the central-government budget would increase by the combined population (2.31) and economic (1.28) growth rates that were used in the simulations, this would lead to central-government revenues of 824 FCFA billion in 2025 (up from 281 billion in 2000). This is still a conservative estimate, as central government revenues grew at more than eight percent annually between 2001 and 2006. The share of fertilizer tax exemptions in total government revenues would thus amount to less than three percent in 2025.

II-4.1.7 Conclusions

Increasing population and land scarcity are the two most important driving factors influencing the food balance of Benin. Despite the rapid pace of both trends, no absolute land scarcity is likely to emerge in Benin in the next two decades, and thus no scarcity of food. Land use planning and conservation efforts, along with planning for road or irrigation infrastructure, will have to find a compromise between spreading the burden of increasing demand for cropland among regions and types of landscape while conserving existing cropland reserves such as forests, savannas, and wetlands (*bas-fonds*) as much as possible.

In their quest to achieve food and income security for their families, farmers themselves constantly adjust to changes in the ecological and economic environment: in the face of deteriorating prices for cotton, the areas for maize and cassava were increased, and cashew trees, producing a cash crop, have been increasing their share of cultivated area. However, adjusting crop mixes and rotations alone will not suffice to make up for land scarcity, a prominent symptom for which is an ever-shorter fallow period in more densely populated areas. With both labor and land abundantly available, fallow has been the most important tool for soil fertility conservation over centuries. With land becoming scarce, soil fertility will need to be sustained by the increased use of organic matter, leguminous crops, and mineral fertilizer. The profitability of all of these 'modern' options is still precarious, preventing levels of utilization sufficient to stabilize soil fertility, land use, and food supply. Another problem is that labor is still too cheap to reward labor-saving technical innovations. As long as slashing forest is still cheaper than using fertilizer to arrive at a given level of crop harvested, little change in the current trends can be expected. Sustained higher economic, income, and wage growth would, all other things remaining equal, contribute a great deal to reverse the current trends of excessive cropland expansion in Benin.

References

Adégbidi A, Gandonou E, Padonou E, Océni H, Maliki R, Mègnanglo M, Konnon D (2000) Etudes des filières des intrants agricoles au Bénin (engrais, produits phytosanitaires, semences, matériels et équipements agricoles, fertilisants organiques). Ministère du Développement Rural/Coopération Technique Allemande (GTZ), Initiative sur la Fertilité des Sols (IFS, FAO/World Bank)

Cretenet M (1993) Rapport de mission au Benin. CIRAD, Montpellier

CSPR/AIC (2008) AIC-infos. http://www.aicbenin.org. Accessed 26 January 2010

Dagbenonbakin GD (2005) Productivity and water use efficiency of important crops in the Upper Ouémé Catchment: Influence of nutrient limitations, nutrient balances and soil fertility. Doctoral thesis, University of Bonn, Bonn

Dale WJ (1992) Effects of Forest Management on Soil Carbon Storage. Water Air Soil Poll 64(1-2):83-120

EFMA (2008) Annual report 2006/07. European Fertilizer Manufacturers Association. http://cms.efma.org/EPUB/easnet.dll/ExecReq/Page?eas:template_im=000BC2&eas:dat_im=000C55

FAO (1991) Production Vol. 45. Collection FAO: Statistiques N° 104. FAO, Rome

Gaiser T, Fadegnon B, Cretenet M, Gaborel C (1999) Long-term Experiments on a Tropical Acrisol: Evolution of Soil Properties and Maize Yield. In: Merbach W, Körschens M (eds) Dauerdüngungsversuche als Grundlage für nachhaltige Landnutzung und Quantifizierung von Stoffkreisläufen, pp. 153-156. Umweltforschungszentrum Leipzig-Halle GmbH. UFZ Bericht, Vol. 24

Gruber I (2008) The impact of socio-economic development and climate change on livestock management in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2008/gruber_ina/index.htm

Honfoga GB (2006) Vers des Systèmes Privés Efficaces d'Approvisionnement et de Distribution d'Engrais pour une Intensification Agricole Durable au Bénin. Doctoral thesis, University of Groningen, Groningen

IFDC (2005) L'État du Marché des Intrants Agricoles au Bénin. IFDC, Muscle Shoals, AL

INRAB (2000) Rapport annuel. Cotonou

Mulindabigwi V (2006) Influence des systèmes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin, Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2006/mulindabigwi_valens/0784.pdf

Nye PH, Greenland DJ (1960) The soil under shifting cultivation. Farnham Royal, Bucks

Paeth H, Capo-Chichi A, Endlicher W (2008) Climate change and food security in tropical West Africa – a dynamic-statistical modelling approach. Erdkunde 62(2):101-115

Pieri C (1989) Fertilité de terres de savane. Bilan de trente ans de recherché et de développement agricoles au sud du Sahara. Ministère de la Coopération. CIRAD, Paris

Ruthenberg H (1980) Farming Systems in the Tropics. Third edition. Clarendon Press, Oxford

Srivastava AK, Gaiser T (2008) Biomass production and Partitioning pattern of yam (Dioscorea rotundata). Agric J 3(5):334-337

Toigbe E (2004) Evolution de la production nationale de viande. Rapport d'activités. Direction de l'Elevage, Cotonou

van den Akker E (2000) Makroökonomische Bewertung der Auswirkungen von technischen und institutionellen Innovationen in der Landwirtschaft in Benin. Doctoral thesis, University of Hohenheim, Stuttgart

Williams JR (1995) The EPIC Model. In: Singh VP (ed) Computer Models of Watershed Hydrology, pp. 909-1000. Water Resources Publications, Highlands Ranch

II-4.2 Impacts of Global Change on water resources and soil degradation in Benin

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Abstract

Water availability is subject to high temporal variations in Benin due to the natural inter-annual sequence of the rainy and dry seasons. Even if physical water scarcity does not appear to represent the most important limiting factor, access to water in some parts of the Ouémé catchment is constrained by the low economic capacities of suppliers and users. Scenarios of future water availability and water demand were developed and quantified using the hydrological model UHP-HRU (Universal Hydrological Program – Hydrological Response Unit) and the water management model WEAP (Water Evaluation And Planning system). The results of the hydrological model reveal that the amount of renewable water decreases during the period 2001-2049 in both climate scenarios, which are derived from the IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emissions Scenarios) scenarios A1B and B1. For the same period, a strong increase in domestic, industrial and agricultural demand is expected. Different socio-economic scenarios were computed that suggest water demand will significantly increase in the future. Balancing water availability with water demand shows that the length of the period with local scale water stress may increase up to 10 months per year.

Land use change significantly influences infiltration and surface runoff. Even if the water balance will not be significantly influenced, an increase in erosion risk due to land clearing is expected. The model system SWAT (Soil Water Assessment Tool) was used to evaluate the effects of Climate Change and land use change on soil erosion in the Upper Ouémé catchment. The results show that Climate Change will reduce soil erosion risk due to a decrease in rainfall amounts, but future land use change will cause a significant increase in soil degradation. Therefore, in sub-basins with a high potential of cropland expansion, future sediment yield will be driven by land use change and may therefore strongly increase. In sub-basins with a low potential for cropland expansion and strong reductions in rainfall, future sediment yield may decrease.

Keywords: Hydrological modeling, erosion modeling, water availability, water demand, climate scenarios, land use scenarios, soil erosion, water management modeling, water resources, spatial decision support systems, integrated modeling approach

II-4.2.1 Introduction

Balancing future water availability and water demand requires a thorough understanding of natural processes and social conditions (see chap. I-6 and chap. I-8) as well as plausible scenarios of future economic, demographic, and climatic developments (see chap. II-3). To estimate future water availability, the output of a regional climate model was linked to a hydrological model that also considers land use changes as projected by a cellular automata model (see subsect. II-4.2.2). This results in spatially distributed water availability for a number of scenarios for the Ouémé catchment (discharge gauge Bonou, 49,285 km^2) for the period 2001-2049.

The same scenarios were used to simulate future soil erosion in the Upper Ouémé catchment (see subsect. II-4.2.3) up to the year 2025. The model system SWAT was applied to analyze the development of erosion hotspots in the Upper Ouémé catchment driven by land use change and Climate Change.

In order to link the scenarios of future water availability with future water demand, the results of the UHP-HRU model were used in the water management model WEAP in combination with water demand scenarios (Höllermann et al. 2009). Future water requirements were computed by combining trends in population growth and per-capita water demand. The latter was estimated based on a regional survey among private water users. Furthermore, the need for water for animal husbandry was considered (see subsect. II-4.2.4).

The results and models discussed here were implemented in Spatial Decision Support Systems, which are briefly described in subsection II-4.2.5.

II-4.2.2 Scenarios of land use change and Climate Change: Impact on hydrology and water availability

Environmental changes, such as land use change and Climate Change, have a considerable impact on the water cycle. For future water resources management, it is important to assess the possible impacts of these changes on water resources for a longer time horizon of 20-50 years. As it is impossible to predict the exact developments of climate and land use and their impact on the water resources for such a long time span, scenarios regarding the trends of important drivers are often used in interdisciplinary modeling approaches (see chap. II-3). In these approaches, models from different disciplines, such as climate models and hydrological models, are linked via data exchange or dynamic coupling. As a prerequisite, the models used should be validated for the region and tested for the modeling purpose (e.g., land use change, Climate Change). For the Ouémé catchment, the hydrological model UHP-HRU was used in an interdisciplinary modeling approach (Giertz et al. 2006; see sect. I-6.1). The new model version (UHP-HRU 2.5) was validated for different sub-catchments under different land use scenarios for both

dry and wet years. The spatially distributed results have shown that the model results, particularly surface runoff, are highly sensitive to changes in land use (see subsect. I-6.1.2). In this chapter, the impact of land use change on the hydrology of the Upper Ouémé catchment is analyzed using spatially distributed land use change scenarios by Judex (2008) (see sect. II-4.3). The impact of Climate Change on future water availability was simulated for the two IPCC SRES scenarios A1B and B1 for the whole Ouémé catchment for the period 2001-2049 using downscaled results of REMO (REgional MOdel, see sect. II-3.2).

Land use scenarios

In addition to climate, land use is of utmost importance for the hydrological cycle as it influences surface runoff and evapotranspiration. Because of its importance, it must be considered (see sect. I-6.1). The land use change scenarios on which the hydrological modeling was based were simulated by Judex (2008) using the model XULU/CLUE-S (XULU = eXtenable Unified Land Use modelling platform, CLUE-S = Conversion of Land Use and its Effects at Small regional extent, Verburg et al. 2002) for the Upper Ouémé catchment following the assumptions of the socio-economic scenarios developed by the IMPETUS project (see sect. II-3.3 and subsect. II-4.3.4). These socio-economic scenarios draw three different development paths for Benin. The socio-economic scenario B1, named "Economic growth and consolidation of decentralization," describes a scenario of political stability and economic growth. Socio-economic scenario B2, "Economic stagnation and institutional insecurity", sketches a development path of a continuing and mutually influencing spiral of political destabilization and economic depression. Socio-economic scenario B3, "Business as usual", extrapolates the current trends. A detailed description of these scenarios is given in section II-3.3 and in Speth and Diekkrüger (2006).

The differences between the population projections for these socio-economic scenarios are rather low (see sect. II-3.4; Heldmann and Doevenspeck 2008). The highest population growth was determined for socio-economic scenario B2, while B1 was the lowest. The most distinguishing factor between the scenarios is the degree of intensification in agriculture regulating the per-capita demand for cropland and, therefore, the preservation of the natural forests still existing. For socio-economic scenario B1, an increasing use of fertilizer leads to a significant reduction in the per-capita cropland area (-15% in 2025). For socio-economic scenario B2, the demand for cropland remains constant. For socio-economic scenario B3, it is assumed that the cropland use per-capita decreases with increasing population density but without significant intensification of farm production. These scenarios also differ regarding the degree to which protected forests can be preserved. Due to political stability and the commitment of development agencies for natural resource management, the encroachment of cropland into the protected forest is halted in scenario B1. For scenario B3, this is only the case if the land use intensity remains below a certain threshold. In contrast, land use conversion in scenario B2 is possible in the cent-

ral part of the catchment (*Foret classée de l'Ouémé Superieur*) since governmental institutions are considered very weak, and development agencies have left the area.

As a result of the model XULU/CLUE-S, 25 land use maps on a 250x250-m grid were available for each of the socio-economic scenarios. As input for the hydrological model, the fraction of each land use type was calculated from these maps for each HRU (hydrologic response unit) using the GIS-software ArcMap. For the land use scenarios, the climate of the validation period (1993-2004) was used. The application of the model for a longer period ensured that hydrologic processes in both wet and dry years could be simulated in the considered period.

Figure II-4.2.1 shows the differences in surface runoff from 2000 to 2025 for the three scenarios. All scenarios show an increase in surface runoff in the region

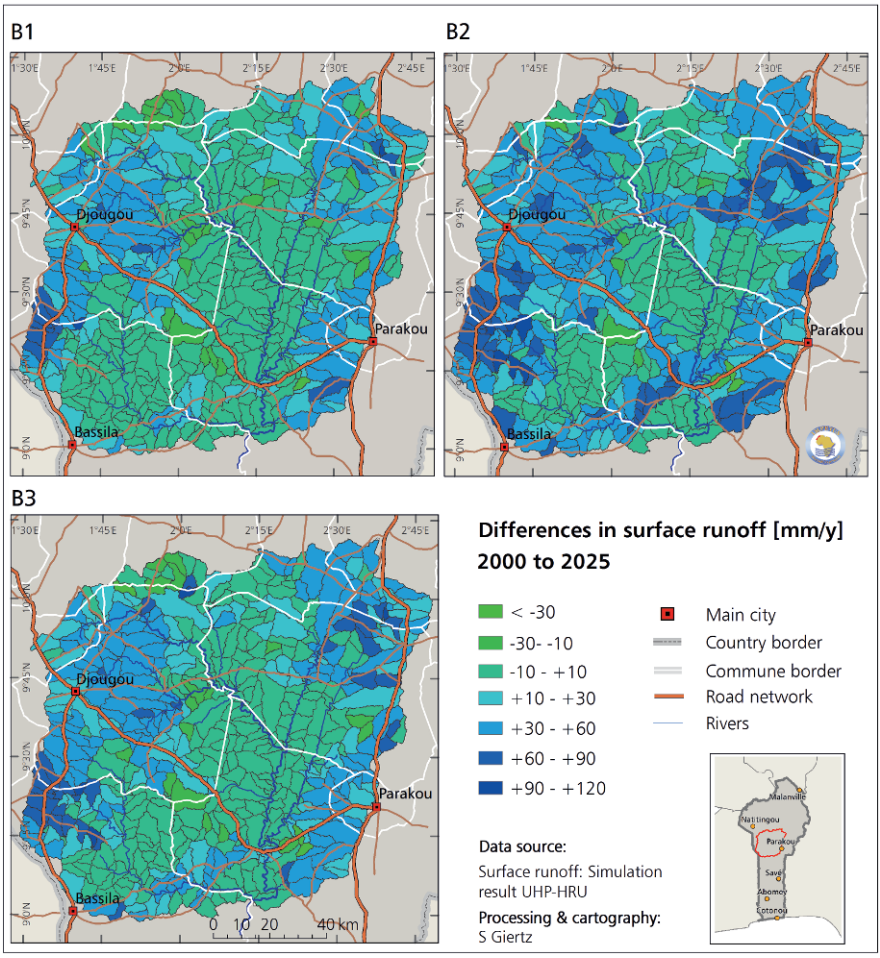

Fig. II-4.2.1: Change in surface runoff from 2000 to 2025 for socio-economic scenarios B1, B2 and B3.

of Djougou and along the roads from Djougou to other villages. The surface runoff is enhanced in all scenarios, especially southwards (toward Bassila). Moreover, the surface runoff increases on the eastern border of the catchment around the cities Parakou and N'Dali. The highest rise is visible in scenario B2. Here, the expansion of cropland and, consequently, the augmentation of surface runoff penetrate into the protected forest of the Upper Ouémé catchment. For socio-economic scenarios B1 and B3, the pattern of change in surface runoff is similar. Almost no increase is observable in the protected forest zone.

Table II-4.2.1: Mean simulated discharge (Qtotal) and surface runoff (Qsurf) for the 2000 land use and land use scenarios B1, B2 and B3 (year 2025) for the Upper Ouémé and the Donga-Pont and Térou-Igbomakoro sub-catchments. Climate data of the period 1993-2004 were used for all simulations.

	2000		B1_2025		B2_2025		B3_2025	
	Qtotal [mm/y]	Qsurf [mm/y]	Qtotal [mm/y]	Qsurf [mm/y]	Qtotal [mm/y]	Qsurf [mm/y]	Qtotal [mm/y]	Qsurf [mm/y]
Upper Ouémé	205	59	220	78	234	93	225	83
Térou-Igbomakoro	245	54	262	86	279	98	270	76
Donga-Pont	294	88	326	132	330	135	329	135

Table II-4.2.1 summarizes the total discharge and surface runoff for the Upper Ouémé catchment and the Térou-Igbomakoro and Donga-Pont sub-catchments for the reference year 2000 and the three scenarios for 2025. The highest discharge and surface runoff of all scenarios was simulated in the Donga-Pont catchment. Because a dense and rapidly growing population forces the conversion of all available unexploited land into cropland in all scenarios, the differences between the scenarios are relatively small for this catchment. The fraction of cropland, and consequently the amount of surface runoff, is relatively similar for all scenarios for the Donga-Pont catchment. By contrast, the differences between the three scenarios are higher for the Térou-Igobomakoro and the whole Upper Ouémé catchments. The fraction of surface runoff nearly doubles in the B2 scenario, while in the other scenarios an increase of 40-60% was calculated by the model. These differences can be explained by the expansion of cropland into the protected forest zones in scenario B2, which covers parts of the Térou-Igbomakoro catchment. This is also true for the whole Upper Ouémé catchment. For the latter, the lowest discharge and surface runoff amounts are determined for the socio-economic scenario B1 due to the lowest growth rate in cropland use.

The scenario results have shown that land use changes in the Upper Ouémé catchment lead to an increase in surface runoff and total discharge, accelerating soil erosion and, consequently, soil degradation, as shown in the study by Hiepe (2008) (see subsect. II-4.2.3). Even though the land use scenarios by Judex (2008) (see subsect. II-4.3.4) are spatially explicit and more differentiated than

simple land use scenarios (e.g., increase in cropland by a factor), the uncertainties have to be taken into account when interpreting the results. As the simulation results of the XULU/CLUE-S model were used in UHP-HRU, the uncertainties involved in both models have to be taken into consideration. The results of this study show more comparable, but not identical, results than the study by Hiepe (2008) for the same scenarios calculated with the SWAT model (see subsect. II-4.2.3). Concerning the uncertainties of the land use model, the simplification of the land use map from twelve classes derived from satellite images to four classes (agricultural land, savannah, forest, settlements) considered in the modeling process must be mentioned.

Climate scenarios

The impact of Climate Change on water availability was simulated for the whole Ouémé catchment using the results of the regional climate model REMO, driven by the IPCC SRES scenarios A1B and B1 (see sect. II-3.2 and Paeth et al. 2009). REMO is a regional climate model with a resolution of 0.5° x 0.5° that is nested in the global circulation model ECHAM5 (European Centre Hamburg Model). The simulations by Paeth et al. (2009) take into account the spatial patterns of future land use change according to FAO. For each scenario, three ensemble runs were simulated from 2001 to 2049, reflecting the uncertainties due to unknown initial conditions (Paeth et al. 2009). According to IPCC (2007), SRES scenario A1B describes a globalized world of rapid economic growth and comparatively low population growth. The use of fossil and non-fossil energy sources is balanced. SRES scenario B1 also characterizes a future globalized world with a low population growth. However, in this scenario, the economic structures change rapidly toward a service and information economy with reduced material intensity and the introduction of clean, sustainable technologies. Consequently, the predicted CO_2 emissions and temperature increases are lower than for the A1B scenario. Both scenarios are rather optimistic compared to the whole SRES scenario family (see sect. II-3.2).

Current climate models cannot correctly represent the climatology of rainfall, but they are more reliable in terms of atmospheric circulation and thermodynamics (Paeth et al. 2005). Therefore, the model results cannot be directly fed into hydrological models. In the case of REMO, the model systematically underestimated the amount and variability of rainfall over West Africa, including a shift in rainfall distribution toward more weak events and fewer extremes (see sect. II-3.2). To address this, so-called Model Output Statistics (MOS) were applied in order to adjust the REMO rainfall data by using other near-surface parameters, such as temperature and sea level pressure wind components (Paeth et al. 2009). A cross-validated multiple regression analysis was used to adjust monthly data to the CRU (Climatic Research Unit) observational dataset (CRU dataset) (Paeth et al. 2009).

As the resolution of the model is relatively coarse (0.5° x 0.5°), a statistical downscaling approach was used to create artificial station data for each rainfall and climate station in Benin. As the hydrological model uses station data as input, this approach allows for a better incorporation of the data. The downscaling algorithm for the precipitation data was based on a probability matching approach that was combined with an orographical and stochastic term. The mean temperature was adapted orographically to a 2-m temperature, which is required in the UHP-HRU model. The relative humidity was also adapted according to the 2-m temperature. The 10-m wind of the REMO grid was downscaled as well, implementing local effects of the orographic roughness. Only the global radiation was directly taken from the REMO grid cell.

Hiepe (2008) has shown that the post-processed results of the REMO model show good correspondence with the measured data, as the mean monthly potential evapotranspiration according to Penman-Monteith (calculated with post-processed REMO data and measured data) could be proved as being highly correlated. The evaluation of rainfall amounts and intensities by Hiepe (2008) have shown that the post-processed REMO results are suitable for hydrological impact studies.

The climate scenarios based on the post-processed REMO results were simulated with the calibrated UHP-HRU 2.5 model for the Ouémé-Bonou catchment for the period 2001–2049. As with the calibration and validation period (see subsect. I-6.1.3), spatially variable rainfall data were used for the climate scenarios for a better representation of the spatial heterogeneity, instead of the mean for sub-

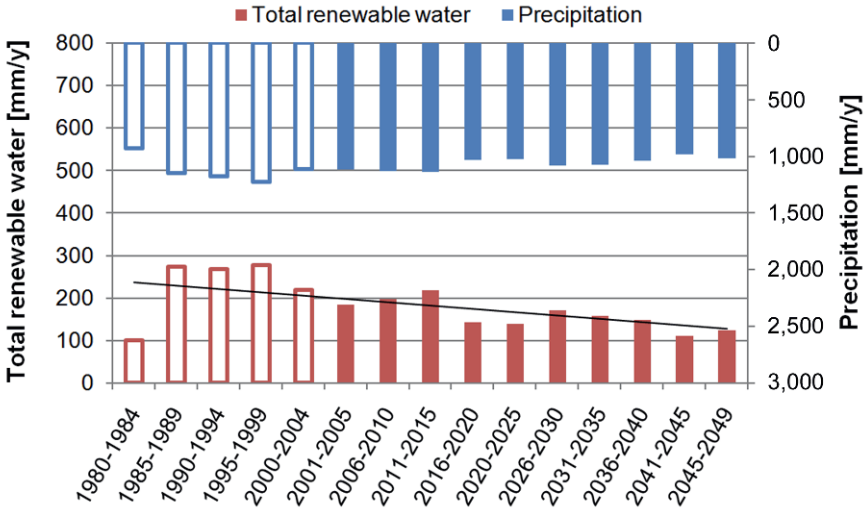

Fig. II-4.2.2: Development of precipitation and renewable water resources (= total discharge + groundwater recharge) in the Ouémé-Bonou catchment for climate scenario A1B simulated with UHP-HRU (mean for of the three ensemble runs; filled bars: UHP-HRU model results using post-processed REMO climate and precipitation data; unfilled bars: UHP-HRU model results using measured climate and precipitation data).

catchments, as in Giertz (2008). In order to take into account the variability of the REMO results, three model runs were simulated for each scenario with the hydrological model UHP-HRU based on the available REMO ensemble runs. For each scenario, the mean of the three runs was taken as the result of the scenario. The land use of 2000 remained constant for the whole simulation period of the climate scenarios.

As the annual variability of rainfall in the region is rather high, and the results of the climate model are not sufficiently accurate to be evaluated within annual time steps, only the results of semi-decades or decades were analyzed. Figures II-4.2.2 and II-4.2.3 show the development of the rainfall and the total renewable water as a mean for semi-decades for climate scenarios A1B and B1. Table II-4.2.2 summarizes the water balance for the reference period 1980-1999 and the five decades of the climate scenarios A1B and B1, as well as the relative change as compared to the reference period.

The results of the hydrological model reveal that the amount of renewable water decreases during the period 2001-2049 in both scenarios. The trend is more extreme in climate scenario A1B. In the latter, the discharge decreases by about 44% in the final decade as compared to the reference period, and a reduction of 52% was determined for the recharge. In the B1 climate scenario, the decrease still amounts to 25% for the discharge and 31% for the recharge. The decrease in renewable water can be explained by a decrease in precipitation and an increase

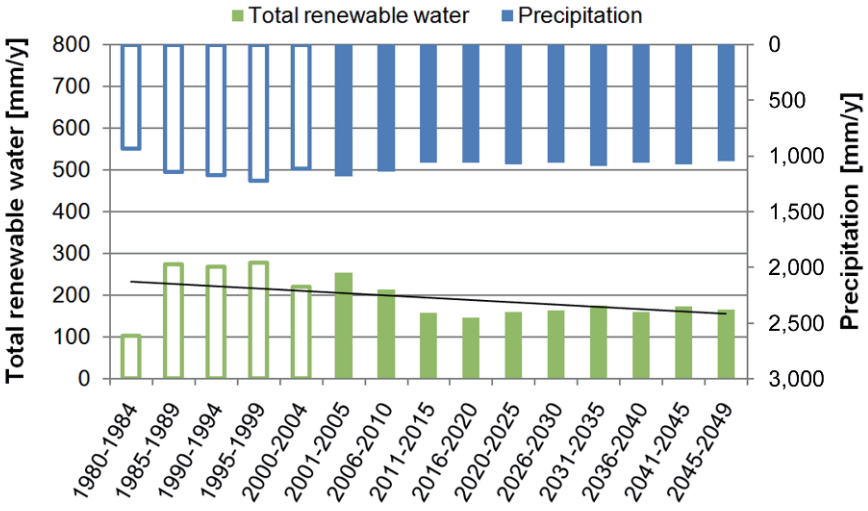

Fig. II-4.2.3: Development of precipitation and renewable water (= total discharge + groundwater recharge) in the Ouémé-Bonou catchment for climate scenario B1 simulated with UHP-HRU (mean of the three ensemble runs; filled bars: UHP-HRU model results using post-processed REMO climate and precipitation data; unfilled bars: UHP-HRU model results using measured climate and precipitation data).

Table II-4.2.2: Mean simulated annual water balance for the reference period and Climate Change scenarios A1B and B1 in the Ouémé-Bonou catchment. The results are averages of the three ensemble runs for each climate scenario. Absolute values and change in % from the reference period are presented.

	Precipitation [mm/y]	Etpot [mm/y]	Etact [mm/y]	Discharge [mm/y]	Recharge [mm/y]	Precipitation [Δ %]	Etpot [Δ %]	Etact [Δ %]	Discharge [Δ %]	Recharge [Δ %]
observed										
1980-1999	1,118	1,727	908	131	99	0	0	0	0	0
Scenario A1B										
2001-2009	1,125	1,953	921	105	84	0.6	13.0	1.4	-20.3	-15.5
2010-2019	1,091	1,971	907	83	83	-2.4	14.1	-0.2	-20.1	-16.6
2020-2029	1,035	1,988	895	83	58	-7.4	15.1	-1.5	-37.0	-41.0
2030-2039	1,078	2,010	909	96	70	-3.6	16.3	0.0	-26.5	-28.4
2040-2049	997	2,053	877	74	47	-10.8	18.8	-3.5	-43.9	-52.2
Scenario B1										
2001-2009	1,159	1,915	908	132	103	3.6	10.9	0.0	0.8	3.7
2010-2019	1,072	1,973	916	90	67	-4.2	14.2	0.8	-31.3	-32.4
2020-2029	1,069	1,972	912	91	67	-4.4	14.2	0.4	-30.8	-31.9
2030-2039	1,079	1,992	908	99	72	-3.5	15.3	0.0	-24.5	-27.4
2040-2049	1,065	2,021	897	98	68	-4.8	17.0	-1.3	-25.2	-31.3

in temperature until 2049 in both scenarios. Due to the higher amount of CO_2 in climate scenario A1B, the increase in temperature is higher than in climate scenario B1. This leads to higher potential evapotranspiration and a stronger decrease in renewable water in scenario A1B. However, figures II-4.2.2 and II-4.2.3 reveal that for both scenarios, the renewable water resources in the last semi-decade are still slightly higher than in the period from 1980-1984 which has been very dry.

In figure II-4.2.4, the spatial patterns of the total renewable water are shown for the periods 1980-1989, 1990-1999 and 2040-2049 for both scenarios. The results demonstrate that in the northern parts of the catchment, the spatial pattern remains constant despite a decrease in the amount of water during the period 2040-2049 as compared to 1980-1989 and 1990-1999. The highest water availability was determined for the northwest of the catchment in the *commune* Djougou, while very low water availability is forecast for the south and southeast of Parakou and for the Nigerian part of the catchment. For the southern part of the Ouémé-Bonou catchment, the spatial pattern changes in the future scenarios compared to the past. While the southern fringe had higher water availabilities in the past, relatively low values were simulated for both future scenarios. However, for the period 1990-1999 and for both scenarios, the lowest values are observable for the *communes* Cove and Zangnanado, which are located in the southern part of

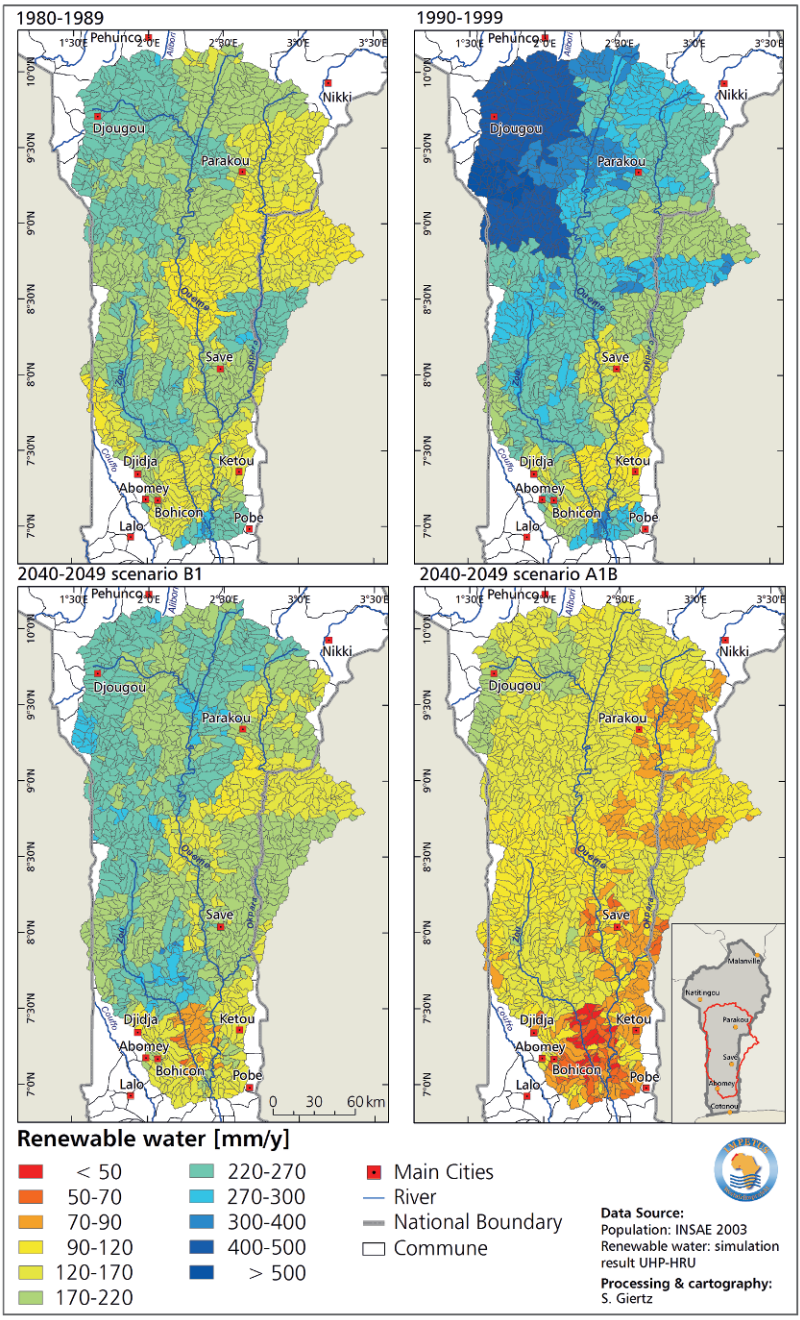

Fig. II-4.2.4: Mean total renewable water resources (discharge + groundwater recharge) for the decades 1980-1989, 1990-1999 and 2040-2049 (scenarios A1B and B1, mean for the three ensemble runs).

the catchment between the Zou and Ouémé rivers. For the A1B climate scenario, only 50 mm of annual renewable water were determined by the model for this region.

The results of this interdisciplinary modeling approach have shown that - following the assumptions of climate scenarios A1B and B1 - a strong decrease in water resources can be assumed for the future in the Ouémé catchment. Götzinger (2007) simulated climate scenarios with the model HBV (Bergström 1995) for the same catchment in the framework of the Rivertwin project. In this project, the ECHAM4 results were statically downscaled without using dynamical downscaling of a regional model. In their scenario analysis, the IPCC scenarios A2 and B2 were chosen. Similar to our study, a strong decrease in discharge was observed for both scenarios.

The results of the scenarios must be interpreted with caution, as many uncertainties are included in the modeling process. In addition to the uncertainties of the hydrologic modeling (e.g., input data uncertainties, model-related uncertainties), the uncertainties of the scenario data must be taken into account. The evaluation of the REMO data from 1960-2000 has shown a good correspondence to the measured data (Hiepe 2008). Therefore, the Climate Change sketched by the REMO model is assumed to plausibly represent the climate development of the region. Nevertheless, global circulation models (GCMs) show no clear rainfall trends for the Guinean Coast (IPCC 2007). The median from the 21 circulation models even show an increase in rainfall of about 2% from the period 1980-1999 to 2080-2099 for the region. The temperature trend is more obvious: all models predict an increase in temperature for the A1B scenario for the same period with an overall median of 3.3 °C for all models (IPCC 2007). As REMO incorporates the land use change in West and Central Africa into the modeling process, the simulated trend of increased temperature and decreased rainfall is more extreme than in simulations of other climate models. Using other IPCC scenarios could have led to significantly different results with regard to future water availability. This must be kept in mind when drawing conclusions from the model results and when defining management strategies.

II-4.2.3 Soil erosion by water in the Upper Ouémé catchment considering land use change and Climate Change

Soil erosion by water deteriorates soil quality and can heavily affect crop productivity in low-input farming systems. The extent of soil erosion in Central Benin is expected to increase in the future due to rapid cropland expansion and more frequent and intense extreme rainfall events due to Climate Change (see sect. II-3.2). On the other hand, mean annual rainfall may be reduced. Erosion models are important tools for studying the effects of land use change and Climate Change on erosive and hydrological processes at the regional scale.

Parameterization of scenarios

After successful application of the time-continuous, semi-distributed SWAT model (Arnold et al. 1993), used to analyze current hydrological and erosive processes in the Upper Ouémé catchment (see subsect. I-6.1.4), future scenarios could be analyzed (see fig. II-4.2.5).

For the three land use scenarios (B1 to B3), land use maps for the years 2005, 2015 and 2025 were used from the XULU/CLUE-S model (Judex 2008; see subsect. II-4.3.4). These reflect an expansion of cropland area by 51-108% until 2025, depending on the scenario. The scenarios assume different cropland demands resulting from the extent of population growth and crop intensification. The XULU/CLUE-S maps with 250 m resolution were disaggregated to accurately represent the fraction of cropland, which is crucial for erosion modeling. The two climate scenarios built on results of the regional climate model REMO (Paeth et al. 2005) based on the IPCC SRES scenarios A1B (global-economy oriented) and B1 (global-sustainability oriented) (see sect. II-3.2). The grid-based REMO-results were statistically post-processed, and the daily rainfall was attributed to individual climate stations. The scenario results were compared to the results of the original model parameterized for the period 1998-2005.

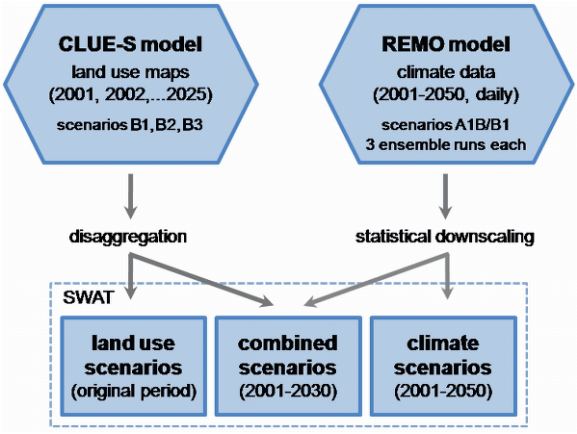

Fig. II-4.2.5: Overview of scenario analysis.

Results of scenario analysis

In the following, the effects of the land use scenarios, climate scenarios, and combined scenarios for the Upper Ouémé catchment are summarized. All land use scenarios increase sediment yield and surface runoff significantly in the Upper Ouémé catchment. All other components of the water balance remain nearly constant (see fig. II-4.2.6, left). By 2025, the sediment yield increases by 42%, 95% and 60% for land use scenarios B1, B2 and B3, respectively. These trends are even more pronounced in the southwest of the catchment, where cropland is rapidly expanding. However, the sediment yields in these areas do not yet reach the current high sediment yields around Djougou and Parakou.

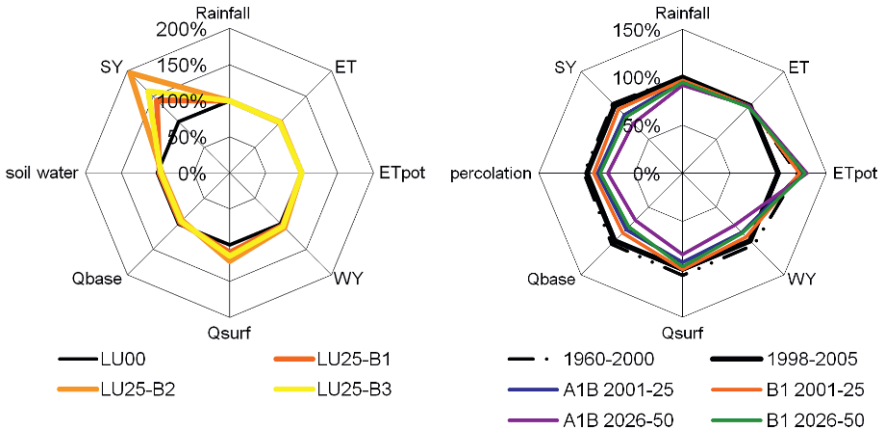

Fig. II-4.2.6: Components of the water balance in the Upper Ouémé catchment for the land use scenarios (left) and the climate scenarios (right) relative to the original model (1998-2005).

The climate scenarios (see fig. II-4.2.6, right) and the combined scenarios for 2001-2025 lead to a more differentiated picture between scenarios. As a result of decreases in mean rainfall of 3% and 4%, climate scenarios B1 and A1B reduce water yield by 6% and 12% and sediment yields by 5% and 14% in the Upper Ouémé catchment, respectively. Despite higher temperatures, actual evapotranspiration remains nearly constant. Surface runoff decreases for the A1B climate scenario and remains nearly constant for the B1 climate scenario.

In the combined scenarios, the negative trend for water yield due to Climate Change is slightly weakened due to land use change. In contrast, sediment yields increase for nearly all combined scenarios by up to 31%, showing the dominance of land use change in most parts of the catchment. In contrast, surface runoff and water yields decrease strongly in the Djougou region, which is most affected by Climate Change and less affected by land use change.

The simulated relative increases in surface runoff and sediment yield for the land use scenarios are similar to those obtained by Busche et al. (2005). In contrast, the climate scenarios from Busche et al. (2005) based on 5-year time slices of REMO for the B1 scenario indicate opposite effects on surface runoff, water and sediment yield than those simulated in this work. This is mainly due to the different rainfall signal given by the more recent, time-continuous REMO simulations.

Figure II-4.2.7 shows the spatial patterns of sediment yield for the business as usual land use scenario and one of the combined scenarios. In addition to the current hotspots of soil erosion in the Djougou and Parakou regions, as well as along the main roads of Djougou-Beterou-Parakou, new hotspots arise in the southern and north-eastern parts of Upper Ouémé. The catchment corresponds to the current deforestation hotspots in the catchment. In total, the scenario analysis for the Upper Ouémé catchment indicates increasing sediment yields and decreasing water yields for

the period 2001-2025 over a wide range of scenarios. Trends in surface runoff depend on the chosen scenario. However, the variability within the Upper Ouémé catchment is large. In sub-basins with a high potential of cropland expansion (e.g., S and SW of the catchment), future sediment yields will be driven by land use change and may therefore strongly increase. In sub-basins with a low potential for cropland expansion and strong reductions in rainfall (e.g., the Djougou region), future sediment yields may decrease. While cropland expansion in the entire Upper Ouémé catchment may slow down in the coming decades, Climate Change impacts will increase with time and show higher variation among the scenarios. The fact that climate models do not yet provide consistent signals for future rainfall trends in West Africa needs to be considered when interpreting the scenario results.

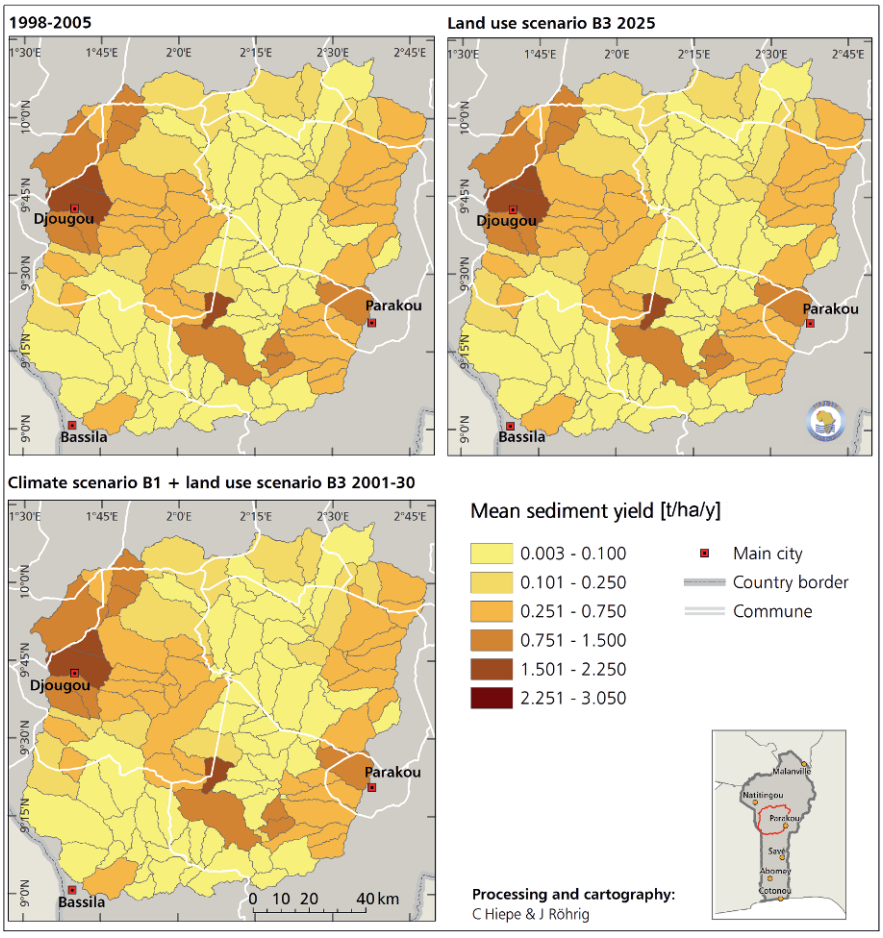

Fig. II-4.2.7: Mean spatial distribution of sediment yield for the original model, the land use scenario B3 (land use 2025, climate 1998-2005) and the climate scenario B1 (2001-2030) combined with land use scenario B3.

II-4.2.4 Balancing future water availability and demand: WEAP application of the Ouémé catchment

Managing water resources efficiently requires a well informed water policy. The information provided to decision and policy makers should therefore be structured in a way that benefits the decision making process. The presentation of water availability and demand in a water balance satisfies these requirements (Sakthivadivel 2006). Therefore the results of the hydrological modeling (see subsect. II-4.2.2) were combined with socio-economic water demand data within the water management model WEAP. Water management models are useful tools for improving water management practices and increasing water security.

The WEAP model

The WEAP system is a demand-, priority-, and preference-driven water management model. It aims at closing the gap between water management and catchment hydrology by addressing water demand and availability simultaneously. Water demand for productive or consumptive purposes and bio-physical factors, such as climate and land cover, vary over time. This is due to factors such as economic growth, increased income, internal migration and urbanization, changes in consumptive attitudes, and Climate Change. This variability complicates the forecasting of future requirements for water provision and, hence, choosing appropriate management practices to meet water demand. With its focus on scenario analysis, WEAP allows the simulation of changes in supply and demand structures, thereby discovering potential shortages and the impacts of different management strategies or development paths on water availability (Yates et al. 2005). As water availability could be transferred from the UHP-HRU model (see subsect. II-4.2.2), the internal modules for calculating water availability in WEAP were not used.

The principle algorithm of WEAP is a spatially-resolved water mass balance calculated on a monthly basis. At every node and link in the system, water supply and demand are balanced. Water demand nodes primarily stand for domestic, industrial or agricultural demand sites as well as flow requirements for hydropower. Groundwater aquifers, reservoirs, and rivers present supply nodes that are connected to the demand sites via transmission linkages. The spatial resolution of the nodes and links is applicable to all scales; however, the resolution highly depends on the questions being asked and data availability.

Applying WEAP to the Ouémé catchment

The hydrological processes of the Upper and Middle Ouémé river basin vary throughout the catchment due to climate and land cover (see subsect. II-4.2.2,

table II-4.2.2). Accounting for these differences required subdividing the catchment into smaller sub-basins. Using the Digital Elevation Model by the Shuttle Radar Topography Mission (SRTM), 27 sub-basins with an average area of about 2,000 km² were obtained. The results of the UHP-HRU modeling provided localized information on surface water flows as well as on groundwater recharge for each of the sub-basins under two different model-based climate scenarios (see sect. II-3.2 and fig. II-4.2.4).

Due to the fractured crystalline basement that dominates most parts of the Ouémé-Bonou catchment (see sect. I-6.1), the integrated groundwater modeling option of WEAP was not applicable. Therefore, a simple storage approach was used to estimate the available groundwater. This benefited from the studies by Faß (2004), El-Fahem (2008), and from the water database BDI (*Banque de Données Intégrée*) of the DGEau (*Direction Générale de l'Eau*, Benin) who have provided valuable information concerning aquifer/maximum well depth and porosity values. Thus, the maximum storage capacity of the groundwater aquifer is 0.46 m³/m² with the saprolite contributing the most (0.4 m³/m²). Furthermore, only the populated areas of the catchment accounted for the available groundwater volume, as large parts of the catchment are not populated (80%) and their resources, therefore, not available for use.

To analyze water demand and supply on the catchment level, it was necessary to disaggregate the information available on the *commune* level to account for different development paths. It was also necessary to aggregate information on the village level to achieve a manageable amount of data. The aggregation took into account affiliation to a *commune* and to a rural or urban district. This approach more than recognizes the recommendations of Wallgren (2006), who suggests applying water demand models at a more local scale.

Water demand scenarios

Benin's water demand has been studied and characterized comprehensively by Schopp (2004), Hadjer et al. (2005), Schopp et al. (2007) and Gruber et al. (2009) (see subsect. I-8.1.1 and 8.1.2). Based on their findings, and taking into account the different development paths of the societal, economic, and ecological scenarios applied by IMPETUS (see sect. II-3.3), water demand scenarios for each sector were developed (Höllermann et al. 2009).

Population growth and economic development are major determinants for future domestic water demand. The combination of population scenarios by Heldmann and Doevenspeck (2008) (see sect. II-3.4), national plans concerning the improvement of water infrastructure (SONEB = *Société Nationale des Eaux du Bénin*), DGEau, and Development Collaborations), and minimum water requirements set by the WHO (2003) and Gleick (1996) allowed the outlining of different water use scenarios. The Millennium Development Goals concerning access to water, for example, are expected to be attained for the business as usual scenario B3 in 2015.

The scenarios of industrial water demand are based on surveys (Schopp et al. 2007) and regional forecast studies by Shiklomanov (1999) and Rosegrant et al. (2002). Annual growth rates are assumed for scenario B3 and B1. The economic growth in scenario B1 also leads to new industry entries, thereby increasing demand.

National agricultural extension plans (MMEH 2000), average population growth rates, and expert interviews by Schopp and Kloos (2006) and Gruber et al. (2009) form the basis of the agricultural water demand scenarios. While scenario B1 shows the highest increase in irrigated area, it remains roughly at the status quo for the scenario B2. The requirements for livestock watering are derived from Gruber (2008) and depend on available grazing areas, economic market conditions and number of livestock. No significant differences in water demand between the scenarios for livestock watering are observed.

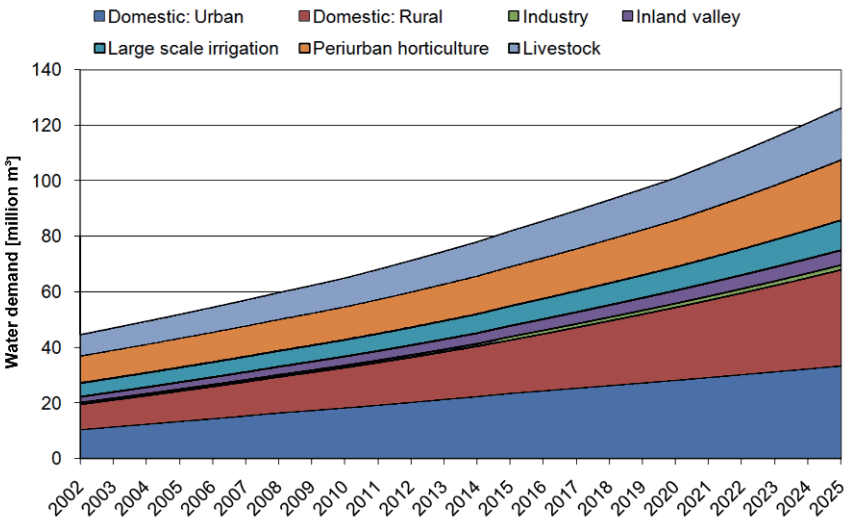

Fig. II-4.2.8: Water demand of the Ouémé-Bonou catchment per user type for the socio-economic scenario B1.

As a result of the different water demand scenarios, demand continuously increases over the simulation period. Consequently, scenario B1 shows the highest growth rates (see table II-4.2.3). Water demand particularly increases for the domestic and agricultural demand sites. Another important use of water is livestock, while industrial water use is projected to remain insignificantly small (see fig. II-4.2.8). While domestic and industrial water demand does not vary throughout the year, agricultural water demand shows a distinct monthly variation, influencing the intra-annual demand. Therefore, water demand is highest from December to March during the dry season, and it decreases with the start of the rainy season. The increased water demand during the dry season intensifies the competition for scarce surface water resources.

Table II-4.2.3: Total water demand [Mm³] for different socio-economic scenarios and for time periods up to the year 2025. Note that the year 2002 is the base year for reference.

Year	Socio-economic scenario B1	Socio-economic Scenario B2	Socio-economic scenario B3
2002	44.47	44.47	44.47
2005	51.77	46.73	50.34
2010	64.84	50.96	60.27
2015	81.77	56.48	71.64
2020	100.92	63.44	83.85
2025	126.06	72.30	98.23

Balancing water demand and supply – WEAP modeling results

The water balance for the Ouémé-Bonou catchment was calculated for the period from 2002 to 2025, with 2002 as the base year for reference (Höllermann et al. 2009). The results show that the different climate scenarios A1B and B1 have a strong impact on water availability. A significant decrease in catchment inflow is observed for the period 2015 to 2025 in climate scenario A1B, while this effect is mitigated in climate scenario B1. The decreasing inflows affect the accessible groundwater storage. While the groundwater aquifers tend to refill completely during the rainy season until 2014, the recharge rate from 2015 on is not high enough, and a decrease in storage is observed, leading to lower groundwater levels during the dry and rainy seasons (see fig. II-4.2.9).

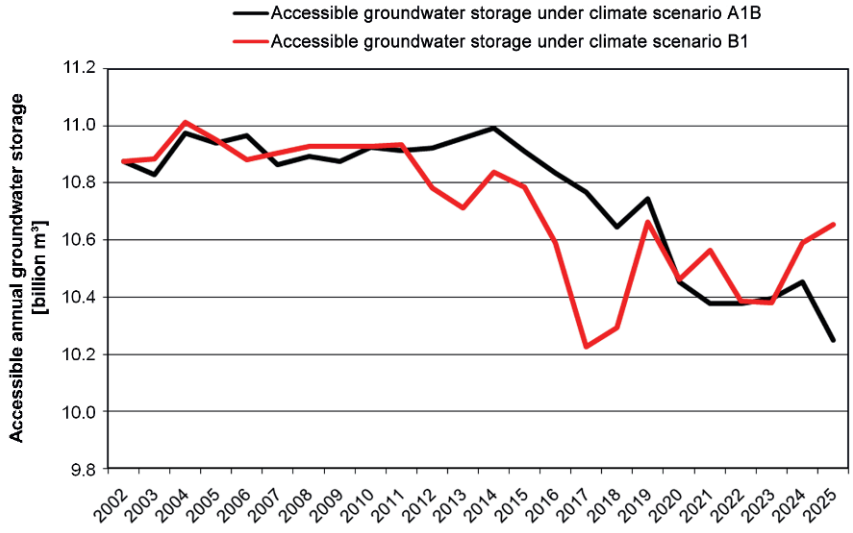

Fig. II-4.2.9: Change in mean accessible groundwater storage due to different climate scenarios.

In general, the surface water inflow into reservoirs varies during the year with little to no inflow from November to May. This typical annual change decreases the storage to a minimum in the months of February to June. With the onset of the rainy season, the storage recovers with its maximum in October. Less catchment inflow aggravates the refill capacity of larger reservoirs. Furthermore, growing water demand increases the pressure on reservoir water. This increase is more significant in climate scenario A1B under the IMPETUS socio-economic scenario B1, presenting the highest water extraction from reservoirs (see fig. II-4.2.10).

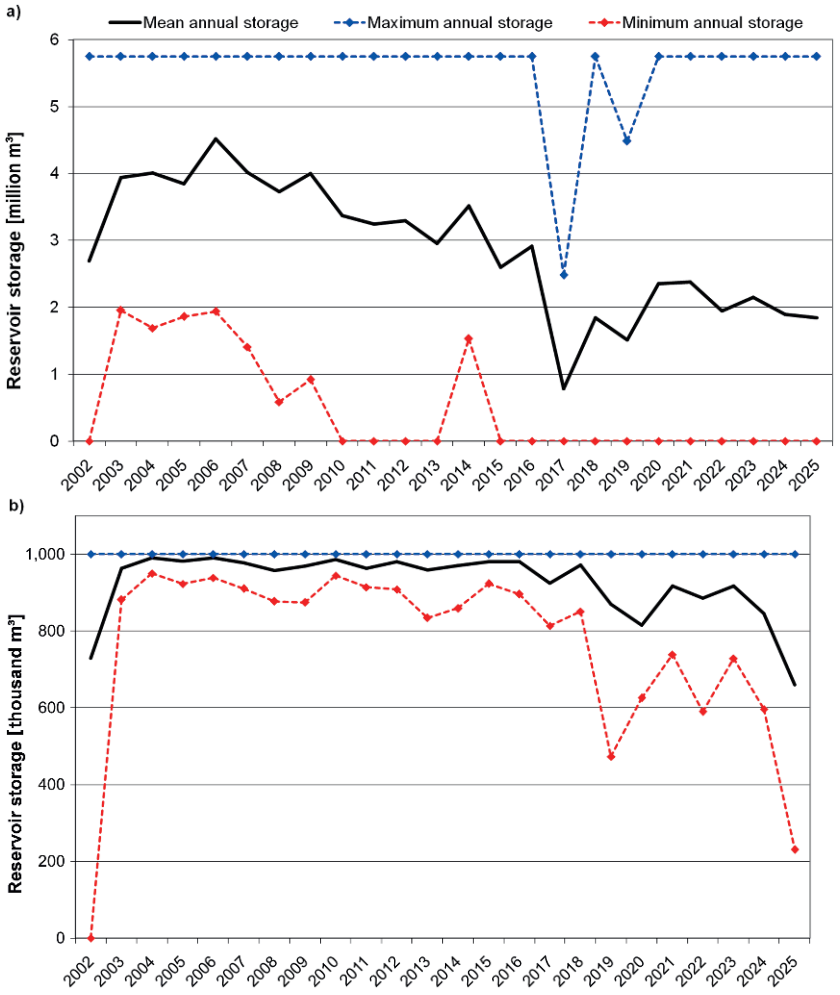

Fig. II-4.2.10: Change in mean reservoir storage under socio-economic scenario B1 and climate scenario A1B. Maxima and minima of storage show the capacity to refill the reservoir and the risk of running dry, respectively. a) Reservoir in Parakou (maximum capacity 5.75 Mm³) and b) reservoir in Savalou (maximum capacity 1 Mm³).

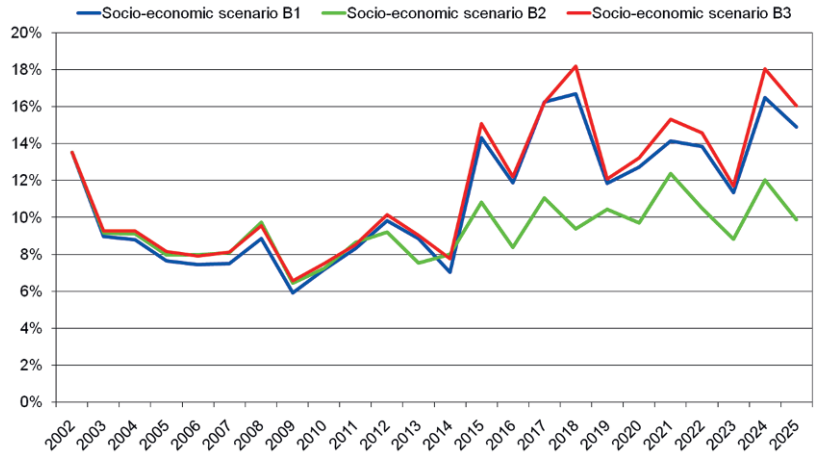

Fig. II-4.2.11: Unmet water demand of the Ouémé-Bonou catchment in percentage of total water demand for socio-economic scenarios B1, B2 and B3.

According to the effects of the climate scenarios, water scarcity is highest in the last decade of the study period. This becomes apparent from the above-average increase in unmet demand in the period 2015–2025 (see fig. II-4.2.11), especially amongst demand sites that rely on water from rivers or reservoirs.

As the availability of surface water follows a monthly variation due to the changes from rainy to dry season, the shortages solely occur during the dry season. While the effects of the dry season with unmet demands can be found for about 8 months per year in the period of 2002–2014, these effects extend to 10 months per year for the period of 2015–2025 (see fig. II-4.2.12).

Water supply security of the Ouémé-Bonou catchment: Interpretation of the WEAP modeling results

WEAP is intended to support the skilled planner for decisions concerning water resources management, but it does not substitute the planner (Yates et al. 2005). As WEAP is a modeling tool that relies on a large number of input parameters and is restricted to a simple water mass balance algorithm, it faces several uncertainties and constraints that stakeholders and policy-makers must account for in order to ensure correct interpretation of the model results.

The water balance results of WEAP imply that water supply security depends strongly on the water sources used. While the available amount of groundwater is potentially high enough to satisfy demand, users relying on surface water from rivers and reservoirs experience shortages. As a result, the different user types relying on surface water are competing with each other. Especially in the northern

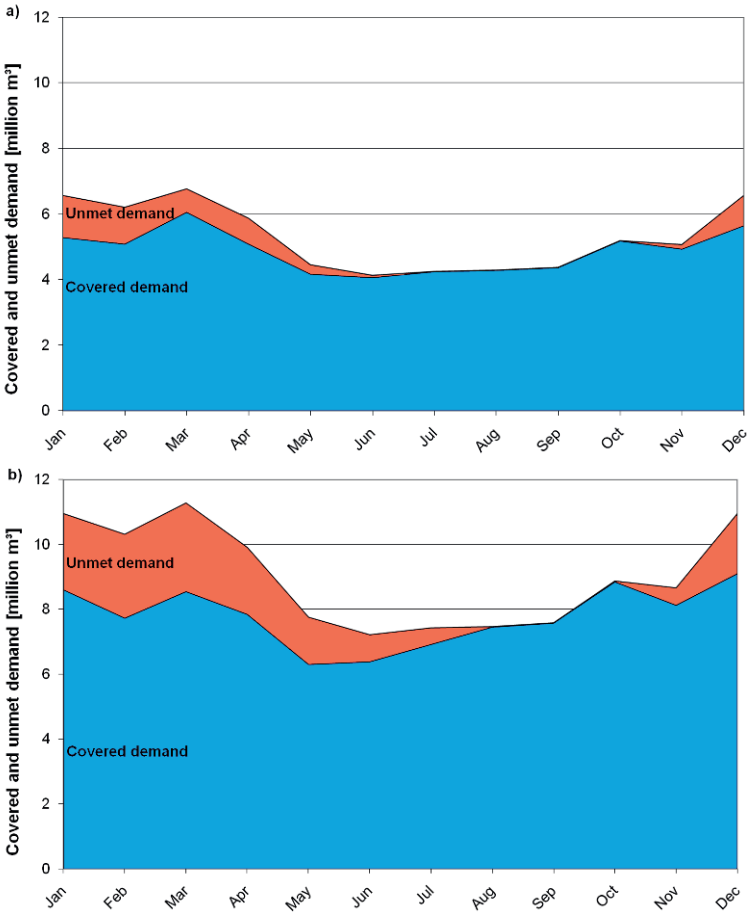

Fig. II-4.2.12: Monthly water demand of socio-economic scenario B1 averaged over the periods 2002-2014 (a) and 2015-2025 (b). The water demand is separated into covered (blue) and unmet (red) demand.

parts of the study area, a distinctive competition between domestic water users and livestock watering is observed. Other competitors for surface water are the peri-urban irrigation sites, which double their demand during the dry season. While the larger reservoirs are intended to mitigate the effects of the dry season and release the pressure on water resources, only the reservoirs in Savé and Savalou hold enough water to bridge the water gap between the seasons.

As a consequence, the water security of the growing number of users relying on surface water is not guaranteed for the whole study period. The situation worsens with the projected changes in climate because the months with no unmet demand decrease from four months (2002–2014) to two (2015–2025). By contrast, the WEAP results imply that the water security for users relying on groundwater

is high. However, these results must be treated with caution. The results of readily available and unlimited groundwater for inland valley irrigation, for example, do not take into account the fact that usually shallow groundwater is used, which also undergoes shortages at the end of the dry season (Giertz et al. 2007). Furthermore, WEAP does not simulate the socio-economic and institutional factors that prevent optimal exploration of groundwater (see subsect. I-8.1.2).

The uncertainties concerning the total amount of groundwater are quite high; however, the observed negative trend in aquifer storage allows qualitative statements about the development of future groundwater availability. First, the reduction in aquifer storage results in a decrease in the groundwater level, and it increases the risk of shallow wells running dry. Second, to mitigate the shortages experienced by declining surface water supply, the pressure on groundwater increases. In turn, this demand accelerates the negative effects on groundwater storage and level, starting a vicious circle.

Even though uncertainties and constraints exist, the WEAP results offer a solid basis for assisting planners in developing recommendations for future water resources management. The scenario analysis with WEAP has revealed potential conflicts over water, the occurrence of shortages, and the development of mitigation strategies. For example, increases in surface water efficiency as well as technical and organizational improvements in the rural infrastructure (e.g., reliable pumps, sufficiently deep wells, and improved management structures) can mitigate current and future shortages in water supply and therefore increase water supply security. However, one has to keep in mind that an improved infrastructure for exploring groundwater might also further deplete the groundwater.

II-4.2.5 Spatial Decision Support Systems for water-related issues: BenHydro and BenEau

Spatial Decision Support Systems (SDSS) help improve the dissemination of research findings to stakeholders (see chap. II-2). The assessment of the future development of water availability and water demand with plausible scenarios is important for integrated water resources management (IWRM). Therefore, the findings concerning water availability and water demand in Benin of the IMPETUS project have been made available through two SDSS systems: BenHydro and BenEau. Technical details concerning the implementation of these SDSSs into the IMPETUS framework can be found in chapter II-2.

The SDSS BenHydro was developed to support the water management of the Ouémé catchment. It enables the user to analyze the impact of environmental changes (e.g., land use, climate) and changes in socio-economic conditions on available water resources and on water demand. It is designed for decision-makers in water management in Benin who have little experience in hydrological modeling. This system includes the UHP-HRU model (see subsect. II-4.2.2).

BenHydro is an interdisciplinary modeling approach that combines climate, land use and hydrologic modeling with water demand. The comprehensive Graphical User Interface (GUI) allows the stakeholder to easily access predefined scenario results, but it also calculates user-defined scenarios by choosing and modifying simulation periods, land use changes, and reservoir usages. The results are not only presented as a table, but also as a graph or map, which improves the visualization of the findings. In addition, it enables comparison of different scenario cal-



Fig. II-4.2.13: Results view of the SDSS BenHydro. The user is able to display different components of the water balance and different scenarios.

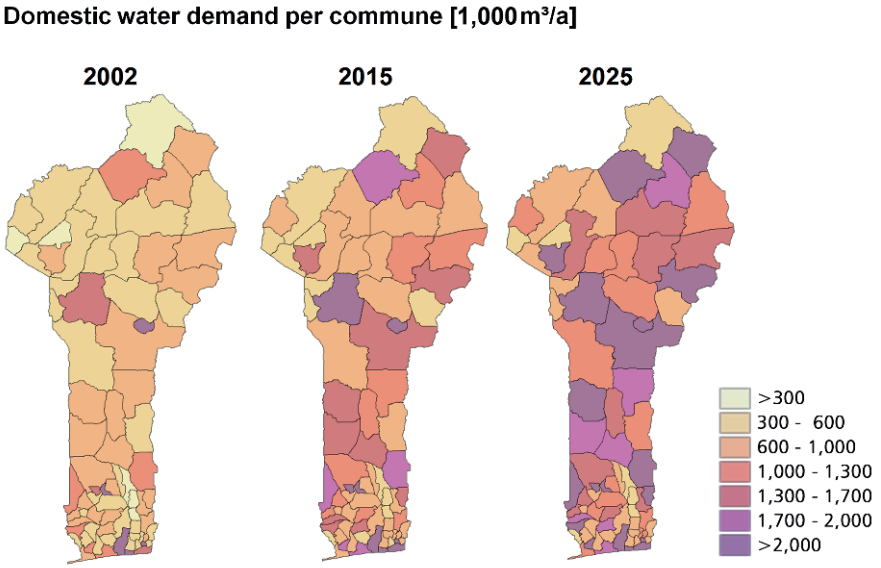

Fig. II-4.2.14: Results view of the SDSS BenEau. The user is able to map, e.g., the development of domestic water demand per *commune* by displaying different steps in time.

culations as well as exporting data for further analysis. Figure II-4.2.13 shows exemplary results for the model run under climate scenario A1B.

The water demand for Benin is calculated in the SDSS BenEau, which is interlinked with BenHydro. BenEau extrapolates the domestic, industrial and agricultural water demand in the course of Benin's socio-economic, climatic and environmental change. Based on the research findings concerning current water demand (see subsect. I-8.1.1), and applying the three IMPETUS scenarios for water demand (see subsect. II-4.2.4), BenEau presents the development of communal water demand from 2002 to 2025 under different socio-economic and environmental conditions (see fig. II-4.2.14). In addition to visualizing the IMPETUS research findings, the user is able to use the baseline data to create their own scenarios by modifying data (e.g., water consumption per head, population growth, access to water sources, number of industries, size of irrigated area). This high flexibility allows a detailed analysis of impacts of different management strategies, thereby providing valuable support for the stakeholder.

The combination of the SDSS BenHydro and BenEau enables decision-makers to balance water demand and availability, which is the focal point for successful and sustainable integrated water resources management.

II-4.2.6 Conclusions

The scenario analysis for the Ouémé catchment and its sub-catchment has shown that Climate Change, as well as land use change, will have a strong impact on hydrology and soil erosion in the region.

While the expansion of croplands leads to an increase of surface runoff, total water yield and soil erosion in the land use scenarios, the climate scenarios show a contrasting trend. The increase of temperature and decrease in rainfall cause a decrease in total available water for both scenarios for the period 2001-2025/2049.

In the combined land use and climate scenarios simulated with the SWAT erosion model, the soil erosion increases, which shows the high impact of land use change. However, the variability of soil erosion within the Upper Ouémé catchment is large.

With the WEAP water management model, it was possible to identify future problems of water supply in the Ouémé catchment by linking water availability with water demand. For the simulated climate scenarios, users relying on surface water from rivers and reservoirs, especially, will experience shortages in the future, while the available amount of groundwater is potentially high enough to satisfy the demand. Here the problems of poor access to the available groundwater must be kept in mind.

The results of the presented studies are useful for supporting water management planning and soil conservation activities in Benin. As the IWRM-strategy is actually implemented in the water policy of Benin, reliable data concerning the development of available water resources and water demand on a catchment level are required. With the results of the water management model WEAP and the SDSS BenHydro and BenEau, these data are provided for planners and decision makers in Benin in a user-friendly way. In order to support soil conservation planning in Benin, the results of the SWAT model have been implemented in the user-friendly SDSS PEDRO (*Protection du sol et durabilité des ressources agricoles dans le bassin versant de l'Ouémé*) (see subsect. II-2.4.1).

References

Arnold JG, Allen PM, Bernhardt G (1993) A Comprehensive Surface-Groundwater Flow Model. J Hydrol 142(1-4):47-69

Bergström S (1995) The HBV model. In: Singh VP (ed) Computer Models of Watershed Hydrology, pp. 443-476. Water Resources Publications, Littleton, CO

Busche H, Hiepe C, Diekkrüger B (2005) Modelling the effects of land use and climate change on hydrology and soil erosion in a sub-humid African catchment. Proceedings of the 3rd International SWAT Conference 2005. http://www.brc.tamus.edu/swat/3rdswatconf/SWAT%20Book%203rd%20Conference.pdf. Accessed 25 August 2009

El-Fahem T (2008) Hydrogeological conceptualisation of a tropical river catchment in a crystalline basement area and transfer into a numerical groundwater flow model - Case study for the Upper Ouémé catchment in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/el-fahem_tobias. Accessed 25 August 2009

Faß T (2004) Hydrogeologie im Aguima Einzugsgebiet in Benin/Westafrika, Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/fass_thorsten/0384.pdf. Accessed 25 August 2009

Götzinger J (2007) Distributed Conceptual Hydrological Modelling - Simulation of Climate, Land Use Change Impact and Uncertainty Analysis. Mitteilungen Institut für Wasserbau, Universität Stuttgart 164. http://elib.uni-stuttgart.de/opus/volltexte/2007/3349/pdf/Diss_Goetzinger_ub.pdf. Accessed 25 August 2009

Giertz S (2008) Assessing the Impact of Climate and Land Use Change on Future Water Availability in the Ouémé Catchment. In: Judex M, Thamm HP (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 37-38. Department of Geography, University of Bonn, Bonn

Giertz S, Steup G, Gaiser G, Srivastava AK (2007) Nutzungspotential von Inland-Valleys im Oberen Ouémé Einzugsgebiet. In: Integratives Management Projekt für einen Effizienten Umgang mit Süßwasser in Westafrika. Fallstudien für ausgewählte Flusseinzugsgebiete. Achter Zwischenbericht, pp. 80-91. http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/IMPETUS_Zwischenbericht_2007.pdf. Accessed 25 August 2009

Giertz S, Diekkrüger B, Jaeger A, Schopp M (2006) An interdisciplinary scenario analysis to assess the water availability and water consumption in the Upper Ouémé catchment in Benin. Adv Geosci 9:3-13

Gleick PH (1996) Basic Water Requirements for Human Activities: Meeting Basic Needs. Water Int 21:83-92

Gruber I (2008) The impact of socio-economic development and climate change on livestock management in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2008/gruber_ina/1388.pdf. Accessed 25 August 2009

Gruber I, Kloos JR, Schopp M (2009) Seasonal water demand in Benin's agriculture. J Environ Manage 90(1):196-205

Hadjer K, Klein T, Schopp M (2005) Water consumption embedded in its social context, northwestern Benin. Phys Chem Earth 30:357-364

Heldmann M, Doevenspeck M (2008) Population projections for Benin until 2025. In: Judex M, Thamm HP (eds.): IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 105-106. Department of Geography, University of Bonn, Bonn

Hiepe C (2008) Soil degradation by water erosion in a sub-humid West-African catchment a modelling approach considering land use and climate change in Benin. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/hiepe_claudia.
Accessed 25 August 2009

Höllermann B, Diekkrüger B, Giertz S (2009) Bewertung der aktuellen und zukünftigen Wasserverfügbarkeit des Ouémé Einzugsgebiets (Benin, Westafrika) für ein integriertes Wasserressourcenmanagement mit Hilfe des Entscheidungsunterstützungsmodells WEAP. Hydrol Wasserbewirts 53:305-315

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Judex M (2008) Modellierung der Landnutzungsdynamik in Zentralbenin mit dem XULU-Framework. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/judex_michael.
Accessed 25 August 2009

MMEH [Ministère des Mines, de l'Energie et de l'Hydraulique] (2000) Vision Nationale de l'Eau en l'an 2025 au Bénin. Cotonou

Paeth H, Born K, Girmes R, Podzun R, Jacob D (2009) Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes. J Climate 22(1):114-132

Paeth H, Born K, Podzun R, Jacob D (2005) Regional dynamical downscaling over Westafrica: model evaluation and comparison of wet and dry years. Meteorol Z 14:249-267

Rosegrant MW, Cai X, Cline SA (2002) World Water and Food to 2025: Dealing with Scarcity. IFPRI, Washington DC, IWMI, Battaramulla, Sri Lanka

Sakthivadivel R (2006) Water Balance Studies and Hydrological Modelling for IWRM. In: Mollinga PP, Dixit A, Athukorala K (eds) Integrated water resources management: global theory, emerging practice and local needs, pp. 189-218. Sage, New Delhi

Schopp M (2004) Wasserversorgung in Benin unter Berücksichtigung sozioökonomischer und soziodemograpischer Strukturen - Analyse der Wassernachfrage an ausgewählten Standorten des Haute Ouémé. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/landw_fak/2005/schopp_marion/0526.pdf.
Accessed 25 August 2009

Schopp M, Adams E, Kloos J, Laudien R (2007) Wassernachfrage der Sektoren (Haushalt, Industrie und Landwirtschaft) unter Berücksichtigung möglicher Wasserkonflikte. In: Integratives Management Projekt für einen Effizienten Umgang mit Süßwasser in Westafrika. Fallstudien für ausgewählte Flusseinzugsgebiete. Siebter Zwischenbericht, pp. 102-112.
http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/IMPETUS_Zwischenbericht_2007.pdf. Accessed 25 August 2009

Schopp M, Kloos J (2006) Wassernachfrage der Sektoren (Haushalt, Industrie und Landwirtschaft) unter Berücksichtigung möglicher Wasserkonflikte. In: IMPETUS Westafrika. Integratives Management Projekt für einen Effizienten Umgang mit Süßwasser in Westafrika. Fallstudien für ausgewählte Flusseinzugsgebiete. Siebter Zwischenbericht, pp. 11-118.
http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/IMPETUS_Zwischenbericht_2006.pdf. Accessed 25 August 2009

Shiklomanov I (1999) World Water Resources at the Beginning of the 21st Century. SHI/UNESCO, St. Petersburg

Speth P, Diekkrüger B (2006) IMPETUS West Africa. Second final report for the period 1.5.2003-31.7.2006.
http://www.impetus.uni-koeln.de/fileadmin/content/veroeffentlichungen/projektberichte/FinalReport2003_2006.pdf. Accessed 25 August 2009

Verburg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SSA (2002) Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. Environ Manage 30(3):391-405

Wallgren O (2006) Building and Using Water Demand Models Based on the WEAP Approach. International Conference: Intergrated River Basin Management in Contrasting Climate Zones. http://www.rivertwin.de/assets/final_conference/Session4/Wallgren%20Rivertwin%20final%20conf%2014%20Dec.pdf. Accessed 25 August 2009

WHO [World Health Organization] (2003) The Right to Water. Health and Human Rights Publication Series 3. http://www.who.int/water_sanitation_health/rtwrev.pdf. Accessed 25 August 2009

Yates D, Sieber J, Purkey D, Huber-Lee A (2005) WEAP 21 - A Demand-, Priority-, and Preference-Driven Water Planning Model. Part 1: Model Characteristics. Water Int 30:487-500

II-4.3 Land use and land cover modeling in Central Benin

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Abstract

Land use and land cover is a critical ecosystem component, and changes in land use and land cover have definite and predictable impacts on climate, hydrology, biodiversity and biogeochemical cycles. In Benin, land use and land cover changes will happen at high rates, mainly because of a doubling in the population within the next 30 years. In order to estimate the recent and future land use and land cover changes, the remote-sensing-based regional Land Use Model and Information System LUMIS was developed. LUMIS is a spatially explicit raster-based land use and land cover change model. Based on a logistic regression approach, land use changes are driven by a set of natural, demographic, economic and cultural factors. The parametrization of LUMIS was performed for the period of 1991 to 2002, when detailed ecological and socioeconomic data were available. The model accuracy can be classified as medium-to-high, with an area-under-curve value between 0.7 and 0.9.

The results show that population density and the distance to the road are the dominant driving forces for the conversion of natural savannah areas into agricultural land. Using the IMPETUS land use scenarios B1 (economic growth), B2 (economic stagnation) and B5 (intervention), future land use changes (until the year 2025) were calculated, and the possible consequences on water availability (see sect. II-4.2) and food security (see sect. II-4.1) were analyzed. While the B1-scenario shows a reduced loss of forest land for agriculture, the B2-scenario is characterized by a high deforestation rate. Furthermore, both scenarios show an increased settlement growth, either caused by positive economic development with an increasing number of off-farm jobs in the cities (B1) or by a high rural-urban migration rate, with more and more people moving into the vicinity of the cities in search of work (B2).

Land use and land cover change modeling using LUMIS can be of particular utility in identifying and monitoring the critical development of ‘Hot-Spots’. LUMIS enables the early detection of land use and land cover changes as well as of planning effective measures to counter such changes.

Keywords: Land use modeling, satellite-based land use classification, remote sensing, demographic, economic and climate scenarios, land management

II-4.3.1 Introduction

Human-induced land surface change and anthropogenic Climate Change are the most important forces currently affecting the Earth's ecosystem (Ojima et al. 1994; Vitousek et al. 1997; Foley et al. 2005; Lambin and Geist 2006b). Land cover is a critical component of all ecosystems, and changes in land cover have definite and predictable impacts on the climate (Pielke and Avissar 1990; Bounoua et al. 2002; Feddema et al. 2005; Hegerl et al. 2007), hydrology (Defries and Belward 2000; Costa et al. 2003; Giertz et al. 2005; Lehrter 2006), biodiversity (Dirzo and Raven 2003) and on biogeochemical cycles (Melillo et al. 2003; Fisher et al. 2006). Such changes are largely anthropogenic. Turner et al. (1995) are emphatic: "The land-cover changes of the present worldwide and the recent past are overwhelmingly the result of human action - of activities largely aimed at modifying or converting land-covers for the purposes of production and, to a lesser extent, settlement." The land is subject, however, to natural conditions that may be cyclical and can change abruptly. Such cycles and abrupt changes in natural land conditions may have ominous or even catastrophic consequences in fragile ecosystems. An example of such consequences is the Sahelian droughts of the 1970s and 1980s (Nicholson 2001; Hulme 2001).

Anthropogenic land cover changes may have a number of important negative ecosystem and human resource impacts. In extreme cases, these impacts may be catastrophic (e.g., a deforested mountain side may cause land slides). Often, the changes occur slowly or subtly and are only noticeable if they require costly rehabilitation measures (e.g., persistent soil erosion). Many effects of land use changes are apparent principally at local or regional scales, but when considered in combination, they have increasingly important global impacts. Humans make long-term use of ecosystems for the production of foodstuffs, building materials, water and land ecosystem services (ecosystem goods and services). The critical issue becomes, therefore, how to continue these activities (Foley et al. 2005) in sustainable ways. This issue is a focus of important international programs and a critical component of ongoing scientific research and human development efforts. Examples of past and current development efforts include the International Geosphere-Biosphere Program (IGBP), the International Human Dimensions Research Program (IHDP), the Land use and Land cover Change Project (LUCC) and the Global Land Project (GLP).

The science involving land use and land cover change needs further development and a deeper understanding to accurately describe and predicatively model the highly complex variety of relationships and interactions with other Earth system compartments. An interdisciplinary approach to this research is essential to adequately explore human and environment relationships (Kotchen and Young 2007). In addition to remote sensing and Geographical Information Systems-well-established techniques for land use change analysis-new analytical methods of quantitative modeling allow researchers to formalize complex human-environ-

mental processes and interactions (Verburg et al. 2006). Using a modeling approach, it is possible to gain new insights and simulate possible future ecological changes. Combining remote sensing, GIS and quantitative modeling techniques in the study of complex human-environmental processes presents new challenges and offers the possibility of greater scientific understanding. Some of these challenges and possibilities will be explored herein.

Land use and land cover data are often inadequate, incomplete, or non-existent in less developed countries; in Africa, especially, often only fragmentary official land statistics are kept. During the Sahelian droughts, a number of scientific studies of land use were undertaken to explore climate-related issues and the resulting land degradation. A lot of environmental and social data are available from this work (Reenberg and Paarup-Laursen 1997; Mortimore and Adams 1999; Hammer 2001; Warren 2002). There are, however, comparatively few studies focused on the West African 'Middle Belt', the zone of dense tree savannas between the Atlantic coast and the Sahel (Lambin et al. 2003). This region is the focus of the IMPETUS project . Lambin et al. further state in this study that very little quantitative land use and land cover data are available for any African dry forest and/or woodland savanna environment.

In the next 30 years, the population of western Africa will double (Cour and Snrech 1998). In large parts of the region, there will be a critical need for additional agricultural land as agriculture will continue to be the principal regional economy during this period. Crucial decisions regarding the location and extent of agricultural expansion in the region will be necessary and must consider a number of important regional environmental characteristics. For example, although the soils of the savanna zone in the West African 'Middle Belt' are generally not very fertile, recent studies have documented a very high rate of deforestation in forest and savanna areas due to the expansion of agriculture in this region (Braimoh 2003; Wardell et al. 2003). Central Benin is an example of this deforestation and serves as the study site for this research.

Our current research is focused on the regional scale land use change in Central Benin. A number of important localized social and ecological processes are ongoing within this regional environment, and some of these are readily apparent. It is therefore necessary to adopt a hierarchical analytical approach to analyzing land cover change in order to capture these interrelated local processes (Turner II et al. 1995). Regional scale analyses require a different set of geographic boundaries and data from different spatial resolutions than those typically utilized in the previous land use change research (Orékan 2007).

Specifically, the following questions will be addressed:

1. What land covers and land uses are present in the study area and what are their dynamics?
2. What are the dominant social and environmental processes operating in the study area and what (if any) regional differences exist? How can any regional differences in the socio-economic context explain land use and land cover dynamics?
3. What are the quantifiable factors that determine land use patterns and their change?

4. What modeling approaches can be implemented to simulate land use change in the best way?
5. What future development scenarios are possible and how can these be explicitly modeled spatially?

In addition to this introduction, this section is grouped into five subsections. Subsection II-4.3.2 gives a brief overview of the current concepts in land system research. Subsection II-4.3.3 describes the study area and the land use and land cover information detected from remote sensing. Subsection II-4.3.4 introduces the land use and and cover change model LUMIS, including different model runs. Subsection II-4.3.5 shows the three different land use scenarios for Central Benin, as calculated with LUMIS. Finally, subsection II-4.3.6 provides a summary of the findings and an outlook.

II-4.3.2 Concepts in land system research

The growing importance of research on land use and land cover change has its origins in the increased awareness of global environmental change since the 1970s (Lambin et al. 2006a). Otterman, 1974 (cited in Lambin et al. 2006a), highlighted the importance of land surfaces as a crucial factor for a better understanding of the global climate system. Increased scientific understanding of the complex biosphere and atmosphere cycles has been a primary stimulus for research focused on the links between land use change and Climate Change, and the topic of land use and land cover change has become a prominent research field (Houghton et al. 1999; Chase et al. 2000; Feddema et al. 2005; Fisher et al. 2006). In addition to its effects on the global climate, land use and land cover change has stimulated research in biodiversity, hydrology and soil science (for an overview, see Chhabra et al. 2006) and has had direct and indirect effects on ecosystem services (Meyer and Turner II 1994; Vitousek et al. 1997).

Land system research was also stimulated in the early 1980s with the development of, and the focus on, the concept of ecological sustainability, and it was strengthened by the 1987 Brundtland Report (World Commission on Environment and Development 1987). Although, since the beginning of industrialization, the majority of land use and land cover changes have had negative environmental impacts, scenarios for sustaining land resources and the economy became relevant (World Commission on Environment and Development 1987; Raskin et al. 1998; Raskin et al. 2002).

Since 2000, there has been a convergence of the formerly separate branches of sustainability science (Kates et al. 2001; Clark 2007) and land change or land system science (Rindfuss et al. 2004; GLP 2005). The term ‘land system science’ describes a holistic approach that considers the inherent feedback mechanisms in and between the participating sub-systems.

Definitions and some methodological aspects

In order to discuss land system research, it is first necessary to define some important related concepts. The term 'land cover' describes the physical condition of the Earth's surface, often referencing specific physical categories (vegetation, soil or water; see Turner II et al. 1995). Land cover may be of natural origin, such as natural vegetation, deserts or rock outcrops (Cihlar and Jansen 2001). The term 'land use' is used to describe the manner in which the biophysical attributes of land are altered and the purpose of a particular use (Turner II et al. 1995). Examples are settlement areas, pastures, arable land, or transport infrastructure. The terms 'land use' and 'land cover' are often used interchangeably; a specific land use usually takes place within or produces a specific land cover regime, which characterizes the type of use (Turner II and Meyer 1994; Briassoulis 2000; Cihlar and Jansen 2001).

Currently, satellite imagery is used in combination with socio-economic data and other statistical data to generate an understanding of the processes that drive land cover and land use change. By using these heterogeneous datasets, it is possible to analyze the spatial relationships between satellite and statistical data, leading to new and useful analytical approaches (Geoghegan et al. 1998). A critical issue inherent in these approaches is the differing spatial resolutions of the disparate datasets: they often do not match each other and it is necessary to employ data from different observational scales and of different spatial resolutions. This issue is often of importance (and may be a source of problems) in modeling land use and land cover change.

The categorization of different land use and land cover classes plays a key role in the interpretation of remote sensing data. Frequently, classification schemes are exclusive and hierarchical and combine categories of both land cover and land use. While these schemes may accurately characterize a complex reality, they can produce inconsistencies (Jansen and Gregorio 2002). A possible solution to this problem is to avoid utilizing categorical classes, but instead to employ continuous values for certain properties of the land's surface. As an example, global land cover characteristics are described by the 'Vegetation Continuous Fields' data of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor (Hansen et al. 2003).

An assessment of land cover and land use change is essential for a comprehensive analysis of land use systems because the temporal dimension leads to an accurate understanding of the development paths. Land cover and land use changes are closely linked semantically, and land use changes usually result in direct and predictable land cover changes. Urbanization, settlement expansion or deforestation has massive impacts on local or regional biophysical patterns and processes. Such changes are considered to be land cover conversions, and they represent a distinct change from one land cover category to another (Turner II and Meyer 1994; Lambin et al. 2006a). A land cover category may remain constant, however, if the human impacts go beyond the resilience of the ecosystem and be-

come processes of degradation (e.g., overgrazing, land degradation, etc., Turner II and Meyer 1994). Such land cover modifications are usually linked with slow processes and do not lead to a change of the category, but only to a change of the individual parameters, such as species composition, abundance or soil fertility (Turner II and Meyer 1994; Lambin et al. 2006a). Another kind of modification takes place when an area remains under agricultural use, but agricultural processes change or are modified. Such changes (i.e., improved field cultivation or the use of rainwater for irrigation) routinely cause an increase in agricultural intensity (Jansen and Gregorio 2002). Quantifying the impacts of such modifications requires data at much higher spatio-temporal resolutions than those required to identify and characterize land cover conversions (Jansen and Gregorio 2002; Lambin et al. 2006a).

Land use takes place at the interface between society (the 'social system') and nature (the 'ecological system') and is therefore dependent on factors of both systems (Turner II et al. 1995; GLP 2005) (see fig. II-4.3.1).

The expression of a particular land use system is dependant on the region's natural environment and the resulting 'ecosystem services' as well as on certain socio-economic and political decisions regarding that environment. These factors act simultaneously on different spatio-temporal scales and with different intensities. Addressing all of the relevant variables that characterize land use and land cover change is a common and sometimes difficult meta-problem (Briassoulis

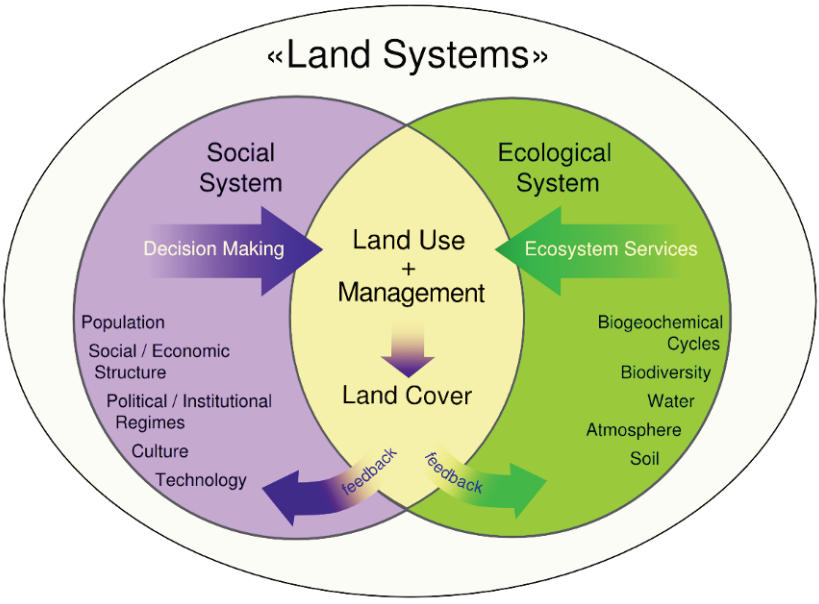

Fig. II-4.3.1: Conceptual framework of land-systems, including interactions and feedbacks between the social and ecological sub-systems (Source: Modified after GLP 2005).

2000). Some important concepts have been developed to address this problem and have been applied successfully.

Causes and explanations

Turner II et al. (1993), Geist and Lambin (2001), and Geist et al. (2006) all employed a well-established scheme that separates the causes of land use and land cover change into 'direct' or proximate causes and 'indirect' or underlying causes. Direct causes include the well-understood mechanisms that are responsible for the conversion or modification of a certain land cover: anthropogenic land use activities, such as agriculture (farming area or extension), forestry (or deforestation) and construction (or settlement expansion) (Geist et al. 2006). Therefore, the focus of these schemes is on humans as active agents who make land use decisions and act accordingly.

Other factors, however, may act indirectly and at several levels simultaneously, so that it is difficult to identify distinct cause-and-effect relationships for specific land use and land cover changes (Geist and Lambin 2001). In contrast to the direct causes, the effects of such indirect causes are not confined to a specific spatial scale or level, but may be influenced by factors operating from the local level (cultural tradition or environmental conditions), the national level (policy framework) or the global level (international commodities prices and trade agreements). Therefore, the accurate analysis of land cover changes requires a synoptic or holistic approach, involving parameters from both the social and natural sciences (Rindfuss et al. 2004; Lambin et al. 2006a).

The causes of land use changes are varied and often specific to certain regions because the uses of environmental conditions and technological capabilities often vary on a regional (or national) basis. In very few cases, such changes can be explained by a mono-causal relationship (Geist and Lambin 2001). In most case studies, the combined effects of several factors must be considered. Generally, there are demographic, economic, technological, institutional, cultural and natural factors that determine land use change (Lambin et al. 2003; Geist et al. 2006). In most cases, land use changes are responses or effects of feedbacks between natural conditions and agricultural systems to changing economic conditions (Lambin et al. 2001; Lambin et al. 2003). However, the individual and societal responses to changing circumstances differ because the perceptions of the conditions by the actors may show a broad range of options ('mediating factors'). For example, generally, the improvement of market conditions is effective for small-scale farmers if they are able to produce cash crops and have access to the market. This example demonstrates that institutional intermediary drivers have different effects on different social groups.

Modeling approaches

Formalized land use and land cover models offer the opportunity to gain a better understanding of observed land use and land cover conversion and modification processes, by analyzing the impacts of specific driving forces on land use and land cover changes. Models are abstractions or simplifications of the real world-the elements that are considered important are included in the model and less relevant aspects are excluded (Wainwright and Mulligan 2003). This leads to a general problem in model development:

" … the reduction and simplification of this real world diversity to serve the purposes of model building is either extremely difficult, or results in a very crude representation of reality. The contrary may happen in other words, models have a very complicated structure that is impossible to handle within the bounds of reasonable time and other resources to provide answers to practical problems." (Briassoulis 2000, sect. 3.1)

In the specific case of the land use and land cover change models, special requirements must be taken into account because of the high complexity of the object:

"Non-cyclic, path-dependent systems show three particularly troublesome properties for modeling: inherent non-predictability, potential non-superiority of outcomes, and structural rigidity."(Turner II et al. 1995)

For this reason, and because no unifying land use and land cover change theory exists, many different model concepts have been developed (Lambin et al. 2006a). However, all of them have the following two basic requirements in common (Veldkamp and Lambin 2001):

1. Identification of the most effective driving forces of land use and land cover change, and;
2. Implementation of a spatial allocation algorithm in order to model spatial effects.

Based on this consideration, a useful land use and land cover change model should provide answers to the following questions (Lambin 2004):

1. What are the socio-economic and biophysical variables that contribute most to the expland cover changes and why?
2. What is the land cover and land use change rate?
3. What places are affected by land use and land cover changes and where are they located?

The spectrum of land use and land cover change models may be characterized according to their conceptual or methodological structures. Verburg et al. (2006) categorize them in groups according to the following features: spatial versus non-spatial; dynamic versus static; descriptive versus prescriptive; deductive versus inductive; agent-based versus pixel-based representation; and, global versus regional models. In addition to these aspects, land use and land cover change models are critically dependant on issues of spatio-temporal scale and extent.

II-4.3.3 Upper Ouémé catchment

Study area

The study area includes the region of the Upper Ouémé catchment in Central Benin (see fig. I-3.2.2). The Upper Ouémé catchment serves as the super test site for all IMPETUS sub-projects, and a comprehensive database has been compiled for the region, including ecological, demographic, and socioeconomic datasets. At 51,000 km², the Ouémé river includes the largest drainage catchment in Benin; the catchment ends in Lac Nokoué at Cotonou, on the West African Atlantic coast. The Upper Ouémé catchment covers 14,366 km² and is located between the cities of Parakou and N'Dali in the east and Bassila and Djougou in the west. In order to correlate land use and land cover changes in the best manner with demographic and socio-economic data, the Upper Ouémé catchment study area was delineated by administrative boundaries (INSAE 2003). These boundaries consist of 50 districts with the individual village as the smallest administrative unit.

Population growth has had a major impact on land use and land cover change in Benin. The last census in Benin (2002) counted 6,770,000 inhabitants. The population growth was 3.25% (INSAE 2003), representing a doubling rate of approximately 21 years. The population growth in Benin is very unevenly distributed, however, showing a strong negative correlation with the existing population density. While the growth rate in the densely-populated southern portion of Benin is approximately two percent, the less densely populated regions in Central Benin show annual growth rates of up to six percent. The high growth rates in these regions are due to heavy migration from the north and south of the country caused by land scarcity in these regions (Doevenspeck 2005).

Remote sensing data

Remote sensing data are routinely employed in land use and land cover analyses. Even for heterogeneous savannah ecosystems, which dominate the Upper Ouémé catchment, satellite image analysis offers excellent and well-established methods for the spatio-temporal characterization of land cover and land use (Jensen 1996; Richards and Jia 2006). Remote sensing data require some amount of preprocessing in order to be effectively used in a land use and land cover change analysis. Preprocessing the multispectral satellite images typically includes GCP-based geo-correction as well as an atmospheric correction and/or a normalization. Since there are significant radiometric differences between different satellite scenes due to seasonal and atmospheric factors, for our analysis only LANDSAT scenes from the same recording time and of the same path were used, preprocessed, and analyzed simultaneously. Scenes from different satellite paths and different recording dates were preprocessed separately.

A multispectral classification approach alone did not produce individual land use and land cover classes of sufficient accuracy. Spectral classification techniques were extended by employing a 'Decision Tree' approach, which included fundamental information regarding the agricultural land use system in use within the study area (e.g., local practices of shifting cultivation). Land use changes were then assessed using a post-classification comparison method (Jensen 1996).

Multi-temporal, high resolution, optical LANDSAT-TM and -ETM + data were used for land use mapping. Gaps in the LANDSAT dataset due to clouds or bush fire smoke within images were filled using ASTER images (see table I-7.1.2). LANDSAT scenes cover 185 x 185 km² at a nominal pixel resolution at a nadir of 30 × 30 m². Reflected radiation is recorded with seven detectors in the spectral region of 0.45 microns to 2.35 microns; one detector also records the thermal radiance at 10.5 microns. The multi-spectral ASTER sensor covers, with its first five channels, the same spectral range as the LANDSAT channels two, five, and seven. A single ASTER image nominally covers a 60 × 60 km² scene at a spatial resolution of 15 x 15 m² (ERSDAC 2005).

This suite of LANDSAT and ASTER data were used to produce an accurate analysis of land use and land cover changes in the Upper Ouémé catchment study area for the period of 1991-2000.

Classification of land use and land cover of the Upper Ouémé catchment

A Maximum-Likelihood classifier (MLC) and Decision Tree classifier (DTC) were selected for the generation of the land use and land cover maps for 1991 and 2000. The training datasets for the classes can be selected from the image interactively by the user in order to include the statistics for each class. Based on the training data statistics, each image pixel is allocated to a particular class according to probability distribution functions or specific thresholds. Since the statistical information for the individual classes often consists of several spectral components, extensive and representative training areas must be defined (Seto et al. 2002). For the classification of the 1991 LANDSAT imagery, the training data were directly collected from the satellite data through image interpretation. For the 2000 LANDSAT data, the training of the supervised classifier was performed based on in situ ground truth information from 170 training data points as well as over 300 validation points (Judex 2008).

We employed a classification scheme based on Reiff (1998), consisting of three principal categories: Type I - Natural Vegetation and Agricultural; Type II - Settlements and Infrastructure, and; Type III - Water Surfaces (see fig. I-7.1.5). Previous work has shown that for very small field sizes (mean field size < 0.3 ha), accurate identification and classification of different crops are not possible (Judex 2008).

II-4.3.4 The land use and land cover change model LUMIS

The development of the new land use and land cover model LUMIS (Land Use Model and Information System) for the Upper Ouémé catchment is based on the XULU/CLUE-S model concept (XULU = eXtendable Unified Land Use modelling platform, Judex 2008 and Schmitz 2005; CLUE-S = Conversion of Land Use and its Effects at Small regional extent, Verburg et al. 2002). The LUMIS is a spatially explicit, raster-based land use change model. For IMPETUS, some model components have been modified and downscaled to the regional scale. The parameterization and validation of the land use model was performed for the period of 1991 to 2000, when detailed land use information was available from satellite remote sensing data. The following description of the change algorithm of LUMIS is based, unless otherwise indicated, on Verburg et al. (2002).

Parameterization

The parameterization of the LUMIS model and the calculation of the probability maps using logistic regression are the basics of LUMIS. Therefore, a set of explanatory variables, or driving forces, must be identified in order to explain and statistically describe the spatial pattern of land use and land use changes. While some driving forces are directly linked to land use (e.g., precipitation), others indirectly affect land use, as is the case for many socio-economic variables (see Geist et al. 2006). In the context of land use modeling, we call such variables mediating factors. Factors such as income, many cultural and religious aspects, political conditions, etc., are often more diffuse and indirectly influence land use practices and intensities. Therefore, the selection of driving forces depends on criteria such as (1) what factors are relevant driving forces and constitute land use patterns, and (2) whether there are any raster data available for these driving forces. A comprehensive overview and discussion on some relevant factors can be found in Meyer and Turner II (1994); Briassoulis (2000); Lambin et al. (2001); Lambin et al. (2003); and Geist et al. (2006). From the numerous important factors, those considered to be the most effective for the study area are listed in table II-4.3.1.

Our regression analysis shows that the main important driving forces, which determine the distribution and change of land use in the Upper Ouémé catchment, are population density (POPDENS), distance to road (DISTROAD), and protection status of forest (PROTAREA).

A quality measure that describes the model's accuracy is the Area Under Curve (AUC) value (Pontius and Schneider 2001). If the area under curve (AUC) is a straight line and exactly diagonal, the area under the curve (or straight) has a value of 0.5 and represents a random model. The steeper the curve, the greater the AUC value and the better is the predictive power of the model. A perfect model would have an AUC value of one. The AUC value for LUMIS reached values

between 0.7 and 0.9. The conversion of logistic regression results into spatial probability maps for each land use item is shown in figure II-4.3.2. For the land use classes of settlement, agriculture, forest and dense savannah and other savannahs, the maps indicate the probability that individual land use existed in 2000.

Model results

LUMIS was developed and calibrated for the period between 1991 to 2000. LUMIS has a temporal resolution of one year and a spatial resolution of 300 x 300 m². The demand for agricultural land was derived from the land cover and land use change analysis between 1991 and 2000. According to the demand for agricultural land, the probability maps were calculated iteratively. Protected forest

Table II-4.3.1: Overview of the explanatory variables for the land-use and land-cover model LUMIS.

Variable	Description	Units
POPDENS	Population Density of rural population within a moving circle (r = 20 km)	E/km²
DISTROAD	Distance to nearest road	m
DISTVILL	Distance to next village	m
DISTCITY	Distance to next city (> 5.000 inhabitants) (along roads)	m
PROTAREA	Forest areas under protection (1 = protected; 2 = unprotected)	(nominal)
SOIL	Soil suitability for agricultural use (1 = poor, …, 5 = very good)	suitability (ordinal)
TOPO	Topographical units (e.g. valley, slope, inselberg)	classes (nominal)
Additional variables		
DISTAGR 1991	Distance to agricultural used areas in 1991	m
DISTFOR 2000	Distance to forest areas in 2000	m
DISTROAD–FOR 2000	Distance between roads and forest areas in 2000	m

areas have been adopted as a restricted zone, and, hence we exclude these areas from the calculations. A comparison between the observed land use and land cover (by satellite data) and the modeled land use and land cover (as a result of LUMIS) for the year 2000 is shown in figure II-4.3.3.

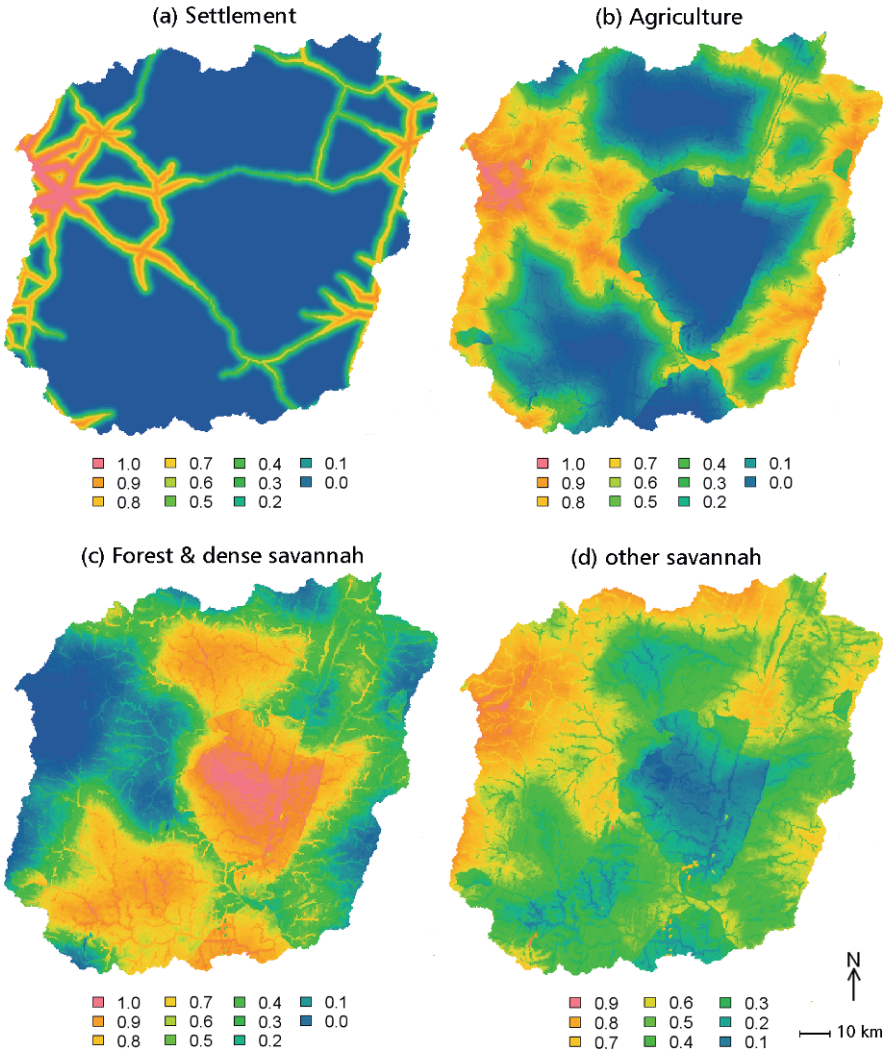

Fig. II-4.3.2: Probability maps of the land-use classes of settlement, agriculture, forest, dense savannah, and sparse savannah, as calculated by logistic regression. Each pixel indicates the probability of a certain land-use class that existed in 2000.

With AUC values from 0.7 to 0.9, the results of the logistic regression and the probability maps of the spatial patterns of land use and land cover demonstrate good model accuracies (Pontius and Schneider 2001). For each land use class, a different set of explanatory variables was found. For the land use class called 'settlement', the logistic regression approach identified the population density (POPDENS) and the distance to road (DISTROAD) as the two relevant explanatory variables. Analogously, the regression models were calculated with all of the variables for the other land use classes. It turns out that the socio-economic variables are more relevant as variables describing the natural environment (e.g., SOIL). Agricultural land use is predominately influenced by the variable population density (POPDENS), showing a high positive correlation. In the case of the forest areas, the variable population density shows a strong negative effect. This suggests that the probability for (more) woodlands will decrease with an increasing population density and that woodlands will be converted to the cost of other land uses, especially agriculture. This result clearly demonstrates the indirect relationship between population density and land use.

These results also coincide with the calculations of Manyong et al. (1996) for the farming sector and underline the dominance of population-driven interventions on land use and the importance of the local scale. With LUMIS, the conversion into agricultural land use can be explained by the variable population density (POPDENS) and the distance to road (DISTROAD). Lower population densities and a greater distance from the road increase the likelihood of land use changes. These findings show that high population pressure and road construction in tropical regions does not always have the highest impact on land use changes as widely postulated (Angelsen and Kaimowitz 1999). This effect is valid only in the inter-

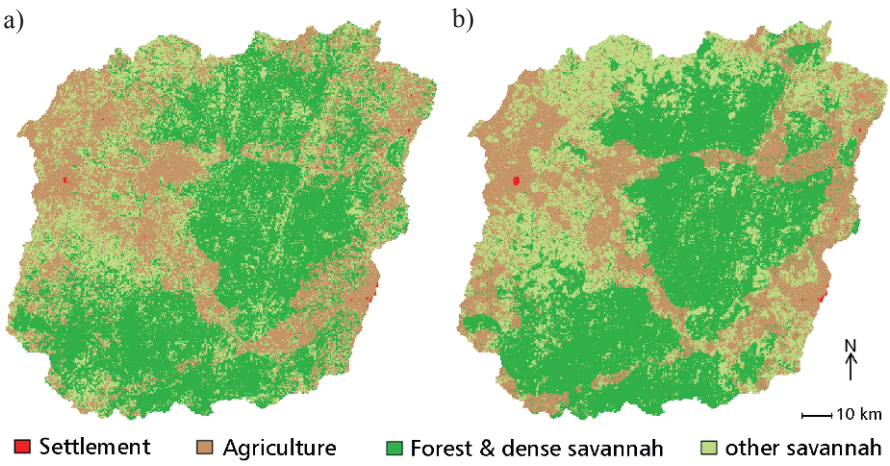

Fig. II-4.3.3: Spatial distribution of land-use and land-cover of the Upper Ouémé catchment for the year 2000, as derived from (a) satellite observations and from (b) LUMIS.

play of all variables used in the model. If the model is run with fewer variables, the effects of the individual variables and the results will change. This fact indicates a strong interaction of the variables employed, but additional interactions remain to be investigated in greater detail (Geist et al. 2006).

Generally, land ownership is another important variable, as can be seen in the protected forest areas (PROTAREA), where agricultural use is not allowed. This leads to a sharp boundary of the land use patterns in the statistical models (using the probability maps). The explanatory variables of the natural soil suitability for agricultural production (SOIL) and relief units (TOPO) show generally weak effects on the probability of all of the models. The simulation of the distribution of the land use change is largely determined by the existing neighborhoods. In the immediate vicinity of the two classes, settlement and agriculture have an increased probability of change, as was confirmed by LUMIS. For scenarios of future land use changes, plausible assumptions for the changing drivers are therefore crucially important. These assumptions are the topic of the next subsection.

II-4.3.5 Land use scenarios until the year 2025

In order to estimate the possible consequences of future land use changes on food security, hydrology, biodiversity, etc., land use scenarios are fundamentally important. Scenarios are "plausible views of the future based on 'if-then' assertions" (Alcamo et al. 2006; see section II-3.1). It is thus not predictions but consistent and plausible descriptions of possible future developments under given conditions that highlight the interrelationships among various factors that constitute a system, and its possible occurrences in the future (Raskin et al. 2002). There are various possible path dependencies, according to the choice of actors and the existing framework. Therefore, several scenarios are designed for a problem, offering various alternative future opportunities (Jenkins 1997) and serving as an important information base, especially for decision makers and stakeholders at all levels of government in Benin. To this end, the results of the scenarios can be integrated in decision support systems. The realization of scenarios can be approached in two different methodological ways: qualitative scenarios describing alternative future trends, mostly in text form (i.e., story lines), and quantitative scenarios that are based on numerical modeling with quantitative data (Alcamo et al. 2006).

Definition of scenarios and parameters for LUMIS

In the following sections, the assumptions of different scenarios of land use change are described. In addition to the existing IMPETUS scenarios B1 and B2, one complement intervention scenario (B5) is defined, which exemplifies the im-

pact of infrastructural changes. For a description of the IMPETUS scenarios see subsection II-3.3.2; details of the scenario calculations can be found in Judex (2008).

(B1) Economic growth scenario

Scenario B1 assumes economic growth and an anchoring of decentralization, i.e., by improving conditions for the political and socio-economic situation. In this scenario, it can be assumed that the functioning of administrative structures and a continuity in development cooperation is an extension of the (small) agricultural innovations taking place. This permits a higher yield per unit area to be produced, thereby increasing the agricultural land use that will be reduced.

In calculating the agricultural area and population data for Scenario B1, the agricultural area is no longer growing exponentially like population growth, but linearly, as the proportion of cultivated land per person is declining steadily due to increasing population density. This seems, given the observed strong surface expansion, especially in the Upper Ouémé catchment, to be unrealistic for the near future. Therefore, it is assumed that the per capita cultivated area will decrease at half the rate. The assumed progress in resource management is reflected in a reduced loss of forest land for agriculture. Initially, in 2000, nearly 50% of the agri-

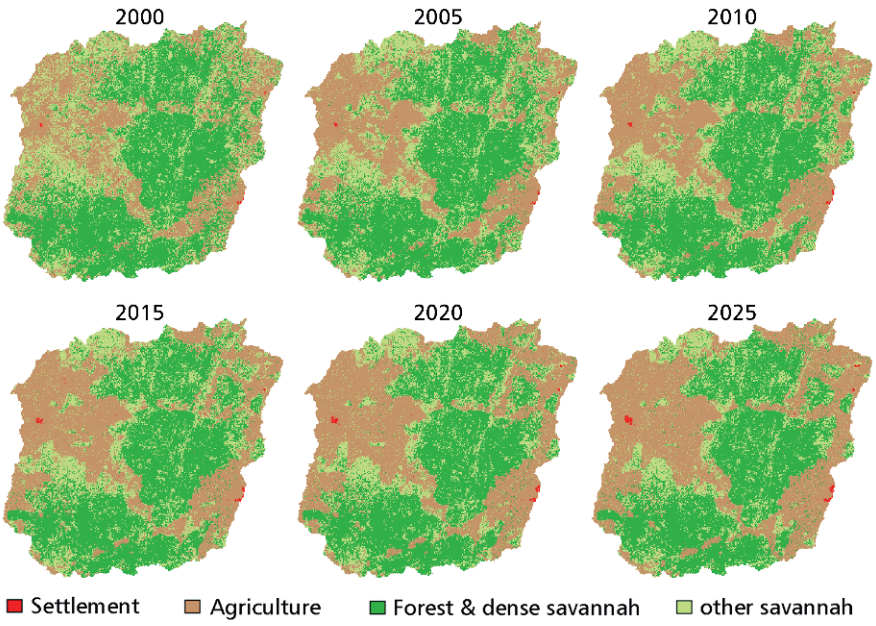

Fig. II-4.3.4: Results of the regional land-use and land-cover change model LUMIS for the IMPETUS *economic growth* scenario B1.

cultural land expansion was won through deforestation; in 2025, it will be only 30%. The settlement area is increasing with the same rate of change (4.5%) as the positive economic development creates more jobs in urban areas (see fig. II-4.3.4).

(B2) Economic stagnation scenario

In contrast to scenario B1, B2 is characterized by economic stagnation coupled with institutional uncertainty. This means that for the agricultural sector, farmers can earn no profits and therefore do not acquire fertilizers to increase production per area unit. Since the inefficient management structures have no control over the protection zones, the large forest areas are increasingly converted into arable land because there are more fertile soils in sufficient quantities available.

The poor resource management and low profit margins in agricultural production will lead to an increased settlement growth, as more and more people in the vicinity of cities look for work. The cities are growing by six percent per year until 2025 (see fig. II-4.3.5).

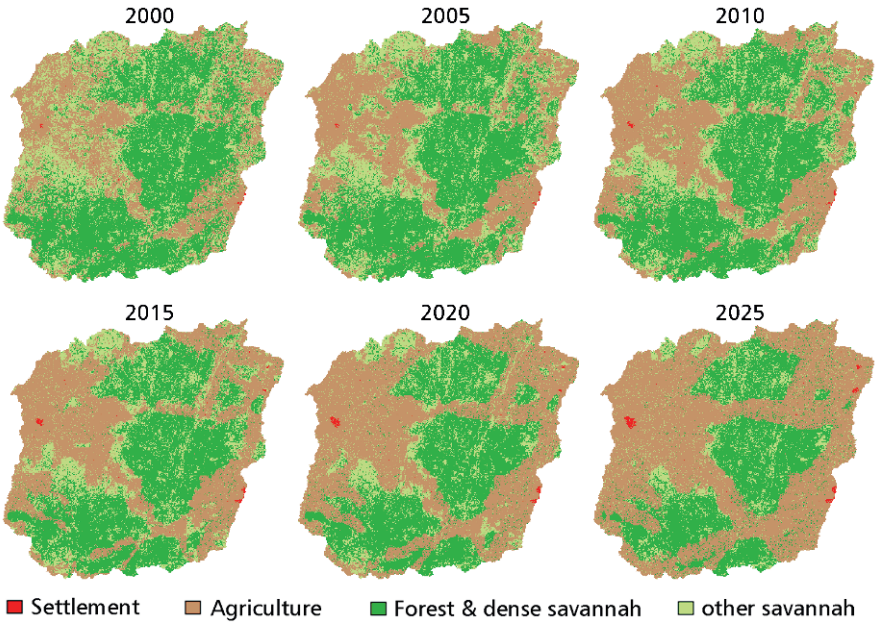

Fig. II-4.3.5: Results of the regional land-use and land-cover change model LUMIS for the IMPETUS *economic stagnation* scenario B2.

(B5) Intervention scenario

Scenarios can also be used to evaluate the impact of a planning measure on the environment. Therefore, a scenario is developed that shows the impact of a hypothetical road construction on the land cover change in the Upper Ouémé catchment. It was assumed that, in 2010, a new road will be developed between Partago and Doguè. This scenario is not unrealistic, as several meetings with representations of the Ministère des Travaux Publics et des Transports documented.

The new road will go through the large, non-protected forest area in the southwest of the Upper Ouémé catchment. As a result, new stretches of agricultural land will emerge along the new road until 2025 (see fig. II-4.3.6), and the larger cities of Parakou and Djougou will not comparably grow as in the other scenarios. Smaller cities will increase disproportionately. That relatively strong increase for agriculture is competing with settlement. In the vicinity of densely-populated, large settlements, the probability of class agriculture is significantly reduced.

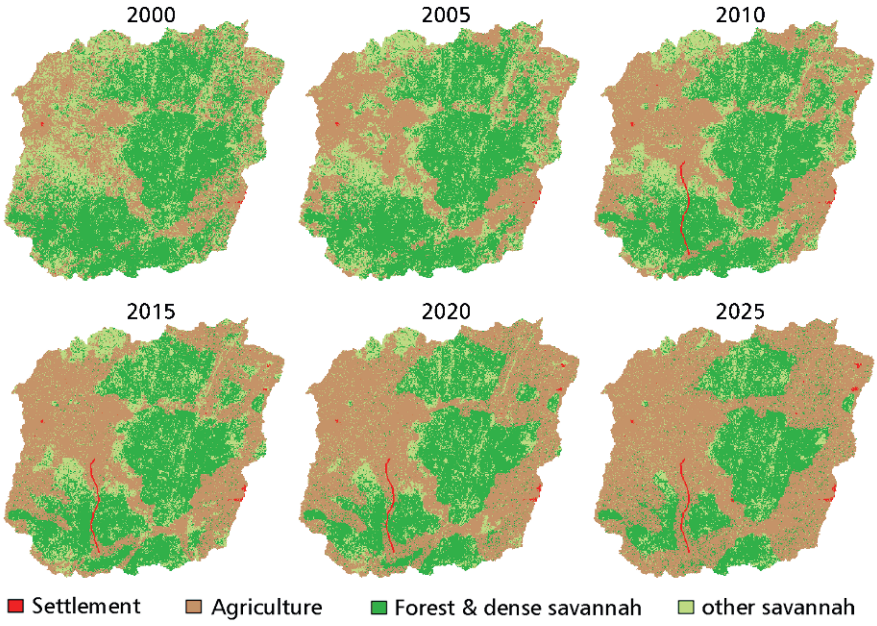

Fig. II-4.3.6: Results of the regional land-use and land-cover change model LUMIS for the IMPETUS *intervention* scenario B5.

II-4.3.6 Conclusions

The LUMIS regional land use and land cover change model was developed in order to simulate the different scenarios of possible future land use changes in Central Benin. The standardized IMPETUS land use and land cover change scenarios were used; they were B1 (Economic growth), B2 (Economic stagnation) and additionally an intervention scenario B5. To calibrate and validate the LUMIS model, past and present land use and land cover changes were derived from historical and contemporary remote sensing data. The three scenarios were calculated on an annual basis and projected for the time period of 2000 to 2025. While the B1 and B2 scenarios were implemented according to the general IMPETUS assumptions, the B5 scenario was based on an exponential population growth parameter and assumed the construction of a new road through a natural savannah area. The B5 intervention scenario demonstrates to regional and national planning authorities the impact of a specific planning measure on future land cover change.

The expansion of agricultural land is the most important land cover change and is predominately based on the driving forces of demographic projections, land use intensity (production system) and assumptions regarding fertilizer use.

In all of the scenarios, population growth is the dominant driver in the transformation of natural bio-ecosystems into agricultural land. Savannah areas with high population densities have a relatively high a priori modification rate into arable land. In addition, the LUMIS model can accurately simulate the conversion of forests into farmland. Deforestation is particularly pronounced in those places where the distance from roads to forest areas is very low and the population density increases over time. Such 'hot spots' of deforestation are found, for example, in the southwest part of the Upper Ouémé catchment, as well as in the northeast, around the communities of Sinende and Bembereke. In the B2 scenario of economic stagnation, the protection of forested areas is assumed to be very weak (e.g., in the *Forêt de l'Ouémé Supérieure* area), and LUMIS produces a high conversion rate under that scenario as well.

Overall, the results of the LUMIS dynamic regional modeling experiment show a pronounced dependency on the starting conditions (definition of the scenarios) and on the scale of a given landscape unit (extent and resolution). It appears that the different starting/boundary conditions lead to the non-linear evolution of the spatial patterns of land use. Further improvements to LUMIS can be expected through the integration of a detailed process understanding at the local/household level (Orékan 2007) as well as the coupling of LUMIS with demographic and agro-economic models (e.g., BenImpact). In addition, further challenges lie in the dynamic coupling of LUMIS to other process-based hydrology, regional climate and erosion models (see section II-4.2). Such model integration will improve our understanding of the complex interactions in human-environmental systems.

This study not only produced detailed information regarding land use dynamics in Central Benin, but also provided an opportunity to demonstrate how spatially explicit data for future land use changes can be obtained by remote sensing. The procedures create accurate and useful results and can be considered as an important method for sustainable resource managment by providing a basis for discussions and developement activities. LUMIS modeling can also be of particular utility in identifying and monitoring critical development 'hot-spots' for the early detection of land use and land cover changes as well as planning effective measures to counter such changes.

References

Alcamo J, Kok K, Busch G, Priess JA, Eickhout B, Rounsevall M, Rothman DS, Heistermann M (2006) Searching for the future of land: Scenarios from the local to global scale. In: Lambin EF, Geist H (eds) Land-use and land-cover change. Local processes and global impacts, pp. 138-155. Springer, Berlin, Heidelberg, New York

Andreß HJ, Hagenaars JA, Kühne S (1997) Analyse von Tabellen und kategorialen Daten. Log-lineare Modelle, latente Klassenanalyse, logistische Regression und GSK-Ansatz. Springer, Berlin

Angelsen A, Kaimowitz D (1999) Rethinking the Causes of Deforestation: Lessons from Economic Models. World Bank Res Obs 14(1):73-98

Bounoua L, DeFries R, Collatz GJ, Sellers P, Khan H (2002) Effects of land cover conversion on surface climate. Clim Change 52(1-2):29-64

Braimoh AK (2003) Modeling land-use change in the Volta Basin of Ghana. Doctoral thesis, University of Bonn, Bonn. http://www.zef.de/fileadmin/webfiles/downloads/zefc_ecology_development/ecol_dev_14_text.pdf. Accessed 12 November 2009

Briassoulis H (2000) Analysis of land use change: Theoretical and modeling approaches. Regional Research Institute, West Virginia University, The Web Book of Regional Science. http://www.rri.wvu.edu/WebBook/Briassoulis/contents.html. Accessed 12 November 2009

Chhabra A, Geist H, Houghton RA, Haberl H, Braimoh A, Vlek PL, Path J, Xu J, Ramankutty N, Coomes O, Lambin EF (2006) Multiple impacts of land-use/cover change. In: Lambin EF, Geist H (eds) Land-use and land-cover change. Local processes and global impacts, pp. 71-116. Springer, Berlin, Heidelberg, New York

Chase TN, Pielke RA, Kittel TGF, Nemani RR, Running SW (2000) Simulated impacts of historical land cover changes on global climate in northern winter. Clim Dyn 16(2):93-105

Cihlar J, Jansen L (2001) From Land Cover to Land Use: A Methodology for Efficient Land Use Mapping over Large Areas. Prof Geogr 53(2):275-289

Clark WC (2007) Sustainability Science: A room of its own. PNAS 104(6):1737-1738

Costa MH, Botta A, Cardille JA (2003) Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. J Hydrol 283(1-4):206-217

Cour JM, Snrech S (1998) Preparing for the Future a Vision of West Africa in the Year 2020. West Africa Long-Term Perspective Study. Club du Sahel - OECD – technical report, Paris

Defries R, Belward A (2000) Global and regional land cover characterization from satellite data: an introduction to the Special Issue. Int J Remote Sens 21(6-7):1083-1092

Dirzo R, Raven PH (2003) Global state of biodiversity and loss. Annu Rev Env Resour 28:137-167

Doevenspeck M (2005) Migration im ländlichen Benin. Sozialgeographische Untersuchungen an einer afrikanischen Frontier. Band 30, Studien zur Geographischen Entwicklungsforschung. Verlag für Entwicklungspolitik, Saarbrücken

ERSDAC – Earth Remote Sensing Data Analysis Center (2005) ASTER User's Guide. Part I General (Ver.4.0). Earth Remote Sensing Data Analysis Center – technical report. Tokyo

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The Importance of Land-Cover Change in Simulating Future Climates. Science 310(5754):1674-1678

Fisher T, Benitez J, Lee KY, Sutton A (2006) History of land cover change and biogeochemical impacts in the Choptank River basin in the mid-Atlantic region of the US. Int J Remote Sens 27(17):3683-3703

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz J A, Prentice IC, Ramankutty N, Snyder PK (2005) Global Consequences of Land Use. Science 309(5734):570-574

Geist HJ, Lambin EF (2001) What drives deforestation? A meta-analysis of proximate and unerlying causes of deforestation based on subnational case study evidence. LUCC Report Series No. 4, Louvain-la-Neuve

Geist H, McConnell W, Lambin EF, Moran E, Alves D, Rudel T (2006) Causes and trajectories of Land-use/cover change. In: Land-use and land-cover change. Local processes and global impacts, pp. 41-70. Springer, Berlin, Heidelberg, New York

Geoghegan J, Pritchard J, Ogneva-Himmelberger Y, Chowdhury R, Sanderson S, Turner B (1998) „Socializing the pixel" and „pixelizing the social" in land-use and land-cover change. In: Livermann D, Moran E, Rindfuss R, Stern R (eds) People and Pixels. Linking remote sensing and social science, pp. 51-69. National Academy Press, Washington DC

Giertz S, Diekkrüger B, Junge B (2005) Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. Phys Chem Earth Parts A/B/C 30(8-10):485-496

GLCF (2009) http://www.landcover.org/index.shtml. Accessed 27 November 2009

GLP; Ojima D, Moran E, McConnell W, Stafford Smith M, Laumann G, Morais J, Young B (ed) (2005) Global Land Project. Science plan and implementation strategy. IGBP Report No. 53 / IHDP Report No. 19, Stockholm

Hammer T (2001) Politische Ökologie der Desertifikation. Ein Beitrag zum Erklärungs- und Lösungskomplex im Sahelraum. Geoöko 22:79-90

Hansen MC, DeFries RS, Townshend JRG, Carroll M, Dimiceli C, Sohlberg RA (2003) Global Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Fields Algorithm. Earth Interact 7(10):1-15

Hegerl G, Zwiers FW, Braconnot P, Gillett N, Luo Y, Marengo Orsini J, Nicholls N, Penner J, Stott P (2007) Understanding and Attributing Climate Change. In: IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Houghton RA, Hackler JL, Lawrence KT (1999) The U.S. Carbon Budget: Contributions from Land-Use Change. Science 285(5427):574-578

Hulme M (2001) Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environ Change 11:19-29

INSAE – Institut National de la Statistique et de l'Analyse Economique (2003) Troisième récensement general de la population et de l'habitation de fevrier 2002. Synthese des analyses. Cotonou

Jensen J (1996) Introductory digital image processing. A remote sensing perspective. 2nd edn. Prentice Hall, Upper Saddle River, NJ

Jansen L, Gregorio A (2002) Parametric land cover and land-use classifications as tools for environmental change detection. Agr Ecosyst Environ 91:89-100

Jenkins L (1997) Selecting a variety of futures for scenario development. Technol Forecast Soc 55(1):15-20

Judex M (2008) Berechnung von Landnutzungsszenarien für den westafrikanischen Savannengürtel mit Satelliten- und Zensusdaten. Doctoral thesis, University of Bonn, Bonn

Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber HJ, Bolin B, Dickson NM, Faucheux S, Gallopin GC, Grubler A, Huntley B, Jager J, Jodha NS, Kasperson RE, Mabogunje A, Matson P, Mooney H, Moore III B, O'Riordan T, Svedlin, U (2001) Environment and development: Sustainability Science. Science 292(5517):641-642

Kotchen MJ, Young OR (2007) Meeting the challenges of the anthropocene: Towards a science of coupled human-biophysical systems. Global Environ Change 17(2):149-151

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George P, Homewood K, Imbernon J, Leemans R, Li X, Moran E, Mortimore M, Ramakrishnan P, Richards J, Skanes H, Steffen W, Stone G, Svedin U, Veldkamp T, Vogel C, Xu J (2001) The causes of land-use and land-cover change: moving beyond the myths. Global Environ Change 11(4):261-269

Lambin EF, Geist H, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu Rev Env Resour 28:205-241

Lambin EF (2004) Modelling land-use change. In: Wainwright J, Mulligan M (eds) Finding simplicity in complexity, pp. 245-254. Wiley & Sons, Chichester

Lambin EF, Geist H, Rindfuss R (2006a) Indroduction: Local processes with global impacts. In: Lambin E, Geist H (eds) Land-use and land-cover change. Local processes and global impacts, pp. 1-8. Springer, Berlin, Heidelberg, New York

Lambin EF, Geist H (eds) (2006b) Land-use and land-cover change. Local processes and global impacts. Springer, Berlin, Heidelberg, New York

Lehrter C (2006) Effects of Land Use and Land Cover, Stream Discharge, and Interannual Climate on the Magnitude and Timing of Nitrogen, Phosphorus, and Organic Carbon Concentrations in Three Coastal Plain Watersheds. Water Environ Res 78:2356-2368

Manyong V, Smith J, Weber G, Jagtap S, Oyewole B (1996) Macrocharacterization of agricultural systems in West Africa: An overview. Band 21, Resource and Crop Management research Monograph. International Institute of Tropical Agriculture, Ibadan

Melillo J, Field C, Moldan B (2003) Interactions of the major biogeochemical cycles. Island Press, Washington DC

Menard S (2002) Applied Logistic Regression Analysis. Sage Publications, Thousand Oaks

Meyer W, Turner II B (1994) Changes in land use and land cover: A global perspective. Cambridge University Press, Cambridge

Mortimore M, Adams WM (1999) Working the Sahel: Environment and Society in Northern Nigeria. Routledge, London

Nicholson S (2001) Climate and environmental change in Africa during the last two centuries. Clim Res 14:123-144

Ojima DS, Galvin KA, Turner II BL (1994) The global impact of land-use change. Bioscience 44(5):300-104

Orékan VO (2007) Implementation of the local land-use and land-cover change model CLUE-s for Central Benin by using socio-economic and remote sensing data. Doctoral thesis, University of Bonn, Bonn.
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2007/orekan_vincent/1084.pdf.
Accessed 12 November 2009

Pielke R, Avissar R (1990) Influence of landscape structure on local and regional climate. Landscape Ecol 4(2-3):133-155

Pontius RG, Schneider L (2001) Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agr Ecosyst Environ 85:239-248

Raskin P, Gallopín G, Gutman P, Hammond A, Swart R (1998) Bending the Curve: Toward Global Sustainability. Band 8, PoleStar Series Report. Environment Institute, Stockholm

Raskin P, Banuri T, Gallopín G, Gutman P, Hammond A, Kates R, Swart R (2002) Great Transition. The Promise and Lure of the Times Ahead. Environment Institute, Stockholm

Reenberg A, Paarup-Laursen B (1997) Determinants for land use strategies in a sahelian agro-ecosystem anthropological and ecological geographical aspects of natural resource management. Agr Syst 53:209-229

Reiff K (1998) Das weidewirtschaftliche Nutzungspotential der Savannen Nordwest-Benins aus floristischer-vegetationskundlicher Sicht. In: Meurer M (ed) Geo- und weideökologische Untersuchungen in der subhumiden Savannenzone NW-Benins. Band 1, pp. 51-86. University of Karlsruhe, Karlsruhe

Richards J, Jia X (2006) Remote sensing digital image analysis. An Introduction. 4th edn., p. 363. Springer, Berlin, Heidelberg, New York

Rindfuss RR, Walsh SJ, Turner BL, Fox J, Mishra V (2004) Developing a science of land change: Challenges and methodological issues. PNAS 101 (39):13976-13981

Schmitz M. (2005) Entwicklung einer generischen Plattform zur Implementierung von Simulationsmodellen am Beispiel der Landnutzungsmodellierung. Master thesis, University of Bonn

Seto K, Woodkock C, Song C, Huang X, Lu J, Kaufmann R (2002) Monitoring landuse change in the Pearl River Delta using Landsat TM. Int J Remote Sens 23:1985-2004

Turner II B, Meyer W (1994) Global Land-use and land-cover change: An overview. In: Meyer W, Turner II B (eds) Changes in land use and land cover: A global perpective. Cambridge University Press, Cambridge

Turner II B, Skole D, Sanderson S, Fischer G, Fresco L, Leemans R (1995) Land-Use and Land-Cover Change Science/Research Plan. IGBP and HDP, IGBP Report No.35, HDP Report No.7, Stockholm, Geneva

Veldkamp A, Lambin E (2001) Predicting land-use change. Agr Ecosyst Environ 85:1-6

Verburg PH , Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SSA (2002) Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. Environ Manage 30(3):391-405

Verburg PH, Kok K, Pontius Jr RG, Veldkamp A (2006) Modeling land-use and landcover change. In: Lambin EF, Geist H (eds) Land-use and land-cover change. Local processes and global impacts, pp. 117-135. Springer, Berlin, Heidelberg, New York

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human Domination of Earth's Ecosystems. Science 277(5325):494-499

Wainwright J, Mulligan M (2003) Environmental modelling. Finding simplicity in complexity. Wiley & Sons, London

Wardell A D, Reenberg A, Tottrup C (2003) Historical footprints in contemporary land use systems: forest cover changes in savannah woodlands in the Sudano-Sahelian zone. Global Environ Change 13(4):235-254

Warren A (2002) Land degradation is contextual. Land Degrad Dev 13:449-459

World Commission on Environment and Development (1987) Our Common Future. Oxford University Press, Oxford

II-4.4 Migration, property rights, and local water resources management in Benin

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Abstract

Management of natural resources in Central Benin is undergoing considerable change. Recent modifications in land tenure and water supply management are taking place in close connection with processes of decentralization, democratization and new policies. Customary tenure principles are highly dynamic and vary from one place to another. The conflict between these socially embedded traditions and national land legislation requires the coexistence of modern and customary land rights, legal pluralism and legal uncertainty. Land disagreements emerge, the purchase of land is problematic and property rights are unevenly distributed. In addition, land has already become scarce in some parts of the region. Degradation affects agricultural production and, therefore, the security of livelihood (see subsubsect. I-8.1.1.4). Laws regarding water are closely related to land tenure and similarly affected by the coexistence of customary land tenure regimes and modern law. Rural water management is particularly affected by a struggle for influence, unclear responsibilities and lack of competencies. During the course of the decentralization process of the water supply, management has been delegated to the communities. The difficulties these communities face in effectively meeting their responsibilities are closely linked to legal uncertainty. Many communities do not release any statistical data. Hence, the IMPETUS Information System LISUOC (Livelihood Security in the Upper Ouémé Catchment) has been developed for this focus group to provide statistically representative data on livelihoods, demographic development and water management.

Keywords: Change, decentralization, democratization, politics, land tenure, water supply management, conflicts, responsibilities local decision making, information system.

II-4.4.1 Introduction

Central Benin, and in particular the Upper Ouémé catchment, is a rural region characterized by high rates of population growth, increasing pressure on natural resources, increasing water demand and degradation of soils. Despite high growth

rates, the population density in the catchment is still below 70 inhabitants per sq km, which allows long fallow periods and thus recovery of soil fertility, at least in some regions. However, the availability of fertile land and water is decreasing due to population increase and possibly also due to climatic changes. This leads to an increase in difficult living conditions for the population concerned.

Climate and demographic scenarios predict that these processes will be exacerbated in the future by many factors, such as a potential overall drying and more extensive dry spells during the rainy season (see subsect. II-3.2.5.) and fast population growth driven by agricultural migration (Doevenspeck 2005). At the same time, profound political and socioeconomic changes are taking place in Benin in general and in the project region in particular. These changes include democratization and decentralization, changes in land tenure in connection with new land policies, radical changes in local tenure systems and in the ethnical and social composition of the population, and reorganization processes in agricultural export production.

This section deals with social, political and economic aspects of change and their interaction with the environment in Central Benin. What is the role of the customary land rights in the overall tenure system concerning land and water resources? How do customary land rights interfere with modern land law? What are the roles of the state, international donors and the recently created communities concerning water supply management in the context of decentralization?

After describing land tenure and the changing legal and political ramifications of the management of land and water, this section will critically examine the most recent changes pertaining to water supply management. Finally, the Information System LISUOC (Livelihood Security in the Upper Ouémé Catchment) is presented, which supports local decision makers by providing information and access to databases on livelihood security, demographic development and water management.

II-4.4.2 Land tenure in the context of national policies

Since the 1990s, Central Benin has been characterized by high population growth rates as it has become a major destination for migrants (see sect. II-3.2). Improvements in the road infrastructures in the region during the 1990s have enhanced chances for a more market-orientated agriculture, which will both entice local people who had emigrated to Nigeria to return and attract migrants from other regions to take their chances in the process of agricultural colonization (Doevenspeck 2005).

Sixty-five percent of the local population cite agriculture as their main economic activity (Hadjer 2008, see sub-subsect. I-8.1.1.4). Land tenure, the relationship among humans with respect to land and water resources, is thus a key aspect of interactions between humans and the environment in the area. Land tenure comprises access to land and water resources, property as well as use rights, transfer of land and resources, and administrative rights. It is composed of a set of rules, which may be written or unwritten, created by societies to regulate behavior (see also FAO

2003). In Benin, land tenure is determined by legal pluralism and legal uncertainty through the coexistence of customary land rights and modern land law. In most rural areas, like the Upper Ouémé catchment, customary land rights still dominate.

Customary tenure principles are an integral part of the social structure and thus inseparable from social relationships throughout rural West Africa, where land is traditionally seen as a common resource. Customary land rights are implemented and arbitrated by customary authorities, whose legitimacy usually derives from prior occupancy (principle of the "first comer" or "first clearance") and the magic/religious alliance with the local spirits, or from conquest (Degla 1998; Delville 2000). The descendants of the mythical or historical community founders, who cleared the area first or who conquered it, inherit their authority over the land, and – at least theoretically – the power to control, distribute and withdraw the use rights within the group and beyond. However, the customary tenure principles are highly complex, dynamic and varying from one place to another.

In some communities a few lineage heads or even one person, such as the so-called earth priest or local chief, maintains the power to allocate to and withdraw use rights from community members and outsiders, while in other communities every community member or even migrants allocate land use rights to outsiders. Yet, in all these cases, land is seen not as an inalienable asset, but rather as a means for the survival of a kin-group comprising the ancestors, the living and the unborn members, and hence represents much more than a means of production.

Indeed, these customary land rights are not in harmony with the national land legislation, based on the colonial land law, which did not take into account customary land tenure. The national legislation focused either on land registration as individual property including use, administration and transfer rights or on nationalization of land. The complexity of customary tenure principles, with diverging and contested use, transfer and administrative rights, has been disregarded until very recently by the national legislature. The consequence is the current coexistence of modern and customary land rights (Heldmann et al. 2008).

In the densely populated area south of Benin, customary land rights are already highly individualized whereas large parts of Central and North Benin are still characterized by common property rights. Commoditization of land is increasing slowly in the areas surrounding the towns, but the purchase of land is still impossible in most rural areas of Central Benin. The consequence of this patchwork of land rights and legal pluralism is legal uncertainty. The purchase of land in both urban and rural areas is problematic, because there is no guarantee that the land in question is or will not be claimed by someone else (Le Meur 2002).

In rural areas, although various forms of land access exist (e.g., heritage, purchase, share-cropping, lease, present, loan), only heritage guarantees unlimited and relatively secure land use rights. Legal uncertainty is thus a particular problem for migrants who cannot inherit rights to land and are forced to borrow land from (customary) landowners. To avoid future property claims by migrants, landowners prohibit them from engaging in any long-term investments such as agroforestry or perennial culture (Mulindabigwi et al. 2008), because trees and some-

times even perennial culture are regarded as symbols of property ownership in large areas of West Africa (e.g., Delville 2000; Le Meur 2002). Agro-forestry, and the planting of cashews in particular, is thus prohibited in large areas of Central Benin (see fig. II-4.4.1).

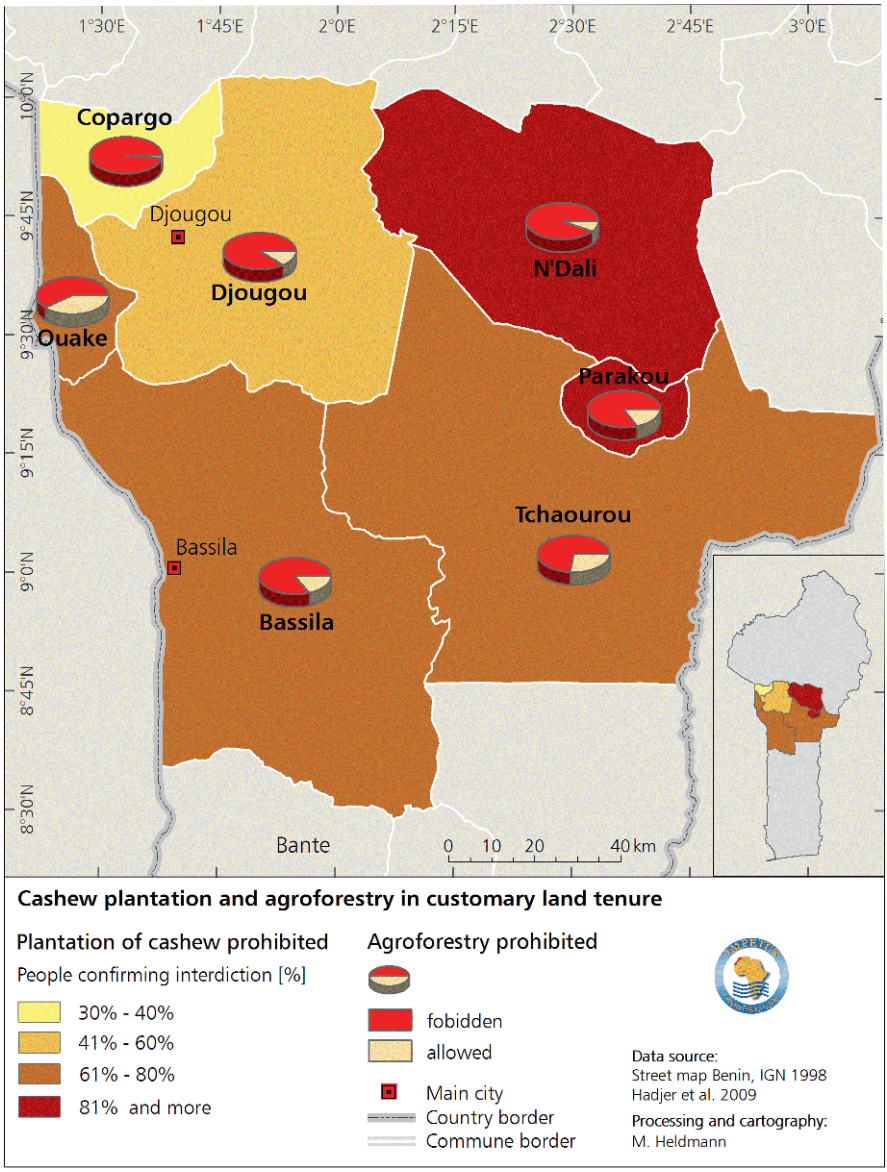

Fig. II-4.4.1: Customary land tenure restrictions on agro-forestry and cashew farming; results from the IMPETUS regional survey.

In situations where property claims are contested and tenure security is lacking, the planting of trees is often impossible. This is also the case in large areas of Central Benin. Furthermore, because no formal contract generally exists between the usufructuary and the landowner, the usufructuary can be removed from the land at any time. For this reason, these non-owners have no incentive toward sustainable land use strategies.

The uneven distribution of property rights is a further problem of land tenure in Benin. In addition to migrants, women cannot inherit land and are thus generally excluded from land possession because of the patrilineal system. In some areas of Benin, rural migrants without secure land rights already constitute the majority of the population. If the commoditization of land increases as it has in South Benin, these people may be deprived of access to credit.

The new rural land law of 2007[1] tried to address the major problems of legal pluralism. The law is considered a basis for the reconciliation of customary and official land rights. The new, simpler rural cadastres on the village level (Plan Foncier Rural) aim to increase legal certainty through documentation of customary land rights. However, land conflicts are also due to inequalities, namely the uneven distribution of land, yet the question of land distribution is not considered in the law.

As long as land is available and as long as degradation is not a major problem, open land conflicts remain rare (Mulindabigwi 2006). But in some parts of the Upper Ouémé region, land has already become scarce and degradation is affecting the agricultural production. Here conflicts over access to land and individualization of land rights — to varying degrees — can already be observed. Private property, however, including full transfer rights of commoditized land, is still rare outside the major towns. Many observers stress that tenure insecurity and legal pluralism constitute a major obstacle for economic development of the region (Degla 1998; Delville 2000; Le Meur 2002), while insiders also emphasize the high degree of flexibility linked to pluralism. The inhabitants of the region, however, are used to high levels of uncertainty and have developed strategies to insure their livelihood (see subsect. I-8.1.1).

In villages like Dogué in the community Bassila, where land is still available, the control and the distribution of land are still held by a few lineage heads and the earth priest. These few lineage heads have the exclusive right to sell wood harvested from the commonly held land. However, any lineage member is free to use a portion of land for farming anywhere on the village's territory.

In villages such as Serou in the community of Djougou, where land has become scarce and degraded, the village territory has been split up among the major lineages and families. This division of village land can be understood as a process of individualization. However, the planting of perennial crops such as cashews is prohibited, because of the fear that these crops could be used to enforce individual claims on land (Mulindabigwi 2006). Thus, we can also observe apparently contradictory tendencies related to individualization within one customary land tenure scheme.

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[1] *Loi n° 2007-03 portant régime foncier rural en République du Bénin.*

In other villages, such as Kpawa in the community Tchaourou, migrants make up the majority of the population. In these cases, locally influential men from the migrant community take over some of the functions of the local elite and the earth priest by distributing land to new migrants (Doevenspeck 2005). Yet, the power of these important men depends on good relationships with the local elite. Furthermore, some local families permit the migrants to settle on the land to extend their own power through patron-client networks. Here, the local population welcomes the migrants because they assume that rapid growth of their village will generate wealth and influence.

II-4.4.3 Water management in times of decentralization

Since 1981 attempts have been made to formulate a clear national policy on water management. Laws regarding water exist and are closely related to land tenure. Their application, however, encounters many difficulties, in particular the coexistence of customary land tenure regimes and modern law, ambiguity of laws, lack of coordination of different actors in the field of water management, etc. In certain cases, particularly near managed water points such as dams, the absence of a legal framework causes conflicts between the users (e.g., between livestock owners and farmers). Managed water points are sometimes provided to the user committees through development projects where the land belongs traditionally to the landowners. Although the land law defines the inland valley as state property, in practice it falls under customary land tenure. In reality, the user committees do not profit from the infrastructures installed on such sites for many years, because the landowners recover the land as well as the managed water points when the projects end.

The laws on decentralization and sector strategies over the period 2005-2015 grant to the community an important role in the management of water infrastructures. This demand-driven approach includes the following: (1) the community is owner of the infrastructures and equipment, (2) the community delegates the water management, which recovers use (production and distribution) and maintenance, (3) the community assumes control and regulation to guarantee the viability and the sustainability of the infrastructures.

On the local level, several actors and institutions compete for political power and influence. Some of them gain their influence through customary offices or through derived political or economic power, while others hold an official public office. Traditional authorities lost much of their influence during the colonial period and more during the Marxist-Leninist rule from 1972 to 1990 when the local aristocracies became associated with exploitation, backwardness and sorcery; but, although the local aristocracies were severely weakened, their power was not completely broken (Bako-Arifari 1999). With the democratization process in the 1990s, traditional authorities have gained in influence, even though they do not hold any

formal public offices, which are held by elected representatives of the villages. Furthermore, the academic elite of the country based in Cotonou exerts a major political influence in their respective native villages through development associations (Doevenspeck et al. 2004).

In addition to these informal actors, officials are formally in charge of the management of natural resources and are generally supported by assistance from various international donor organizations. In rural Benin, these actors are the agents of various centralized public services and the officials of the local districts, the communities that were created in the process of decentralization in the 1990s (see sect. I-3.7). Although the communities hold important legal competencies and responsibilities in the fields of natural resource management and water management in particular, they have neither the funds nor the competencies to assume their responsibilities.

Rural water management is particularly affected by this struggle for influence, unclear responsibilities and lack of competencies. In several laws[2] and application decrees since 1999 and in the governmental sector strategy 2005-2015, the responsibility for the regional rural water supply has shifted from the central state to the communities. This transfer is taking place at a very slow pace. Theoretically, the communities are now entirely responsible for the construction and management of all water supply infrastructures. In reality, the central government and its water agency, however, still play a major role, at least in the construction of the infrastructures and in the allocation of funds.

In March 2008, a new decree has come into effect reducing the (obligatory) co-payment by the local population for the construction of the various water supply infrastructures up to 70% of the cost, depending on the infrastructure. For example, for a water tower the maximum co-payment has been reduced from 5,000,000 FCFA (approx. 7,500 €) to 2,000,000 FCFA (approx. 3,000 €). According to the sector strategy, in the department Borgou 1706 EPE [3] would have to be built for the period from 2008 to 2015. Even if these plans succeed, access to drinking water will not be sustainable unless the water infrastructure is maintained and managed effectively.

Modern rural water supply infrastructures, e.g., water towers and pumps, have to be maintained continuously, implying costs that have to be covered by the water users. In the past and until very recently, the water infrastructure has been managed locally by village committees. These committees have frequently failed to manage and maintain the infrastructures, because they were neither controlled by the water agency of the central state nor did the committees develop internal institutions for control. Today the majority of the water infrastructure is still man-

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[2] *Loi 97-029 du 15 janvier 1999 portant organisation des communities en République du Bénin; loi 2001-07 du 9 mai 2001 portant maîtrise d'ouvrage publique; decrée n° 2001-094 du 20 février 2001 fixant les normes de qualité de l'eau potable.*

[3] EPE (*Equivalent Point d'Eau*): The equivalent drinking water point can supply drinking water for 250 inhabitants (International Monetary Fund 2008) and corresponds, e.g., to one traditional well or one pump and to 0.5 fountain (MMEE and MDEF 2006).

aged collectively at the local level. However, this type of local water management has not proven to promote sustainable and long-term water use. Frequently, the committees meet obstacles that they cannot overcome: conflicts between water users and committees of water management, conflicts between members of these committees, mismanagement of revenues resulting from the sale of water or hesitant repair of breakdowns and malfunctions as shown in figure II-4.4.2.



Fig. II-4.4.2: Because of mismanagement of the water tower in the village of Sirarou, the photovoltaic system is out of order and the population has no access to clean drinking water.

The management of these expensive facilities now has to be organized by the decentralized communities. The community can impose different methods of access and payment for water supply infrastructures:

(1) Collective water supply management, with three different payment methods: payment per water use, monthly lump sums or payment in case of malfunction.

(2) Delegated water supply management, which can be provided by a private company. In this case, a private contractor or a company takes over the responsibilities for functional reliability and cost-effectiveness.

The communities that are now in charge of the water supply management on the regional level advance these arguments to promote private water supply management. The laws define the role of the communities as related to the rural water supply infrastructures as the owners of the water supply infrastructures. Since 2009, the

community has been able to outsource the water supply management (production and distribution) and the maintenance of the facilities. To assure proper management and maintenance of the supply facilities, the community can choose among four types of contracts: (1) a direct contract between a contractor and the community (2) a triple contract with the user committee and a contractor (3) a production contract with a contractor and distribution contract with a user committee[4] (4) a contract with a user committee (MMEE and MDEF 2006).

This flexible system was introduced to improve water supply management and to insure long-term maintenance and sustainability. However, the local population does not really participate in the choice of the water management type and therefore frequently has reservations toward new types of management, because they imply costs that can exclude poor people from a clean water supply.

Furthermore, the communities have difficulty in effectively carrying out their responsibilities in the fields of water management, land use and regional planning, The central government still interferes with these sectors, whether the communities are in charge or not. Moreover, the communities have not yet assumed their roles as independent actors in international cooperation. Virtually no cooperation has been initiated by the communities with international donors. Many international donors, who claim to support the decentralization process, make their agreements with national agencies. Despite insufficient financial means and underqualified staff, international donors also lack information about databases, maps and statistical data from the national census (Mulindabigwi and Singer 2007).

II-4.4.4 LISUOC (Livelihood Security in the Upper Ouémé Catchment): An information system for the decentralized communities

Statistical data and background information from social sciences constitute an important database for local decision makers. However, many communities do not even provide any statistical data to back potential projects for funding. Hence, the IMPETUS Information System LISUOC (Livelihood Security in the Upper Ouémé Catchment) has been developed to provide the communities and other actors with relevant data on livelihood security, demographic development and water management.

The information system is based on three data sets: the survey on livelihoods and anthropological background information on social and economic behavior (module 1, see subsect I-8.1.1), a data set on water resources and insider views on water management practices and conflict arenas (module 2) and data for projection of population growth until 2025 (module 3). These three data sets have been transformed into three and user-friendly modules. The system can also be operated by users with low computer skills. More technical details are presented in subsection II-2.3.4.

[4] In this case, for example, the contractor manages the water tower, sells the water to the committee, which then distributes and sells the water at one or several connected taps.

Module 1: Livelihood security and resource use

This module provides a complex database on local livelihood strategies and resource use. It is based on data compiled by the IMPETUS regional survey, which is described in section I-8.1. Furthermore, it provides detailed anthropological background information on social and economic activity in Central Benin (Hadjer 2009). This information are useful for local planners in the communities as well as for social scientists working in Benin.

The user can query the database by combining variables from the regional survey (see sub-subsect. I-8.1.1.4). The module has also been designed to be operated by users with low computer skills. The user can choose between different themes (work, production, capital, health, gift exchange, medicine) and then select the relevant variables. Furthermore, the system is based on ArcGIS and is equipped with a map panel, showing the results of the queries. The user can choose different spatial and administrative scales (the entire survey area, the communities or the arrondissements). The results can thus be displayed as maps, tables and charts.

Module 2: Water management and institutional change

This module is an important tool for communities and development projects in the field of water management. For example, it visualizes the spatial disparities in the distribution of various water infrastructures (see fig. II-4.4.3 sub-subsect. I-8.1.1.6) and thus assists the user in regional planning of water infrastructures (e.g., to achieve the Millennium Development Goals in the region/community). The module is derived from a database of the various water points (water towers, pumps, modern and traditional wells, ponds, water taps, rivers) of seven communities (Bassila, Copargo, Djougou and Ouaké in the Department of Donga; N'Dali, Parakou and Tchaourou in the Department of Borgou) in the Upper Ouémé catchment (see also SIQEau data base described in sub-

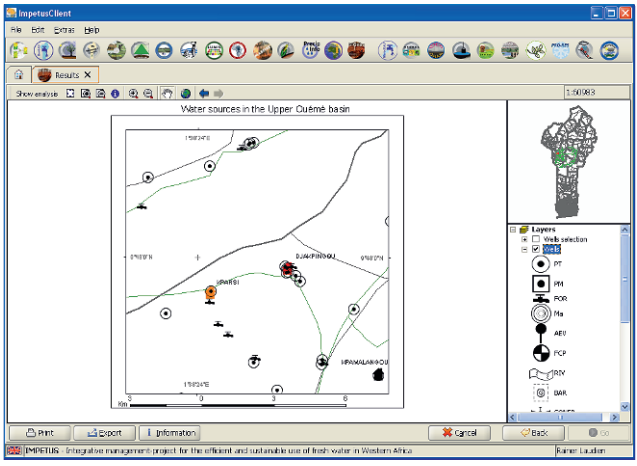

Fig. II-4.4.3: Example of spatial distribution of water infrastructures in the Upper Ouémé basin.

section II-4.5.3). This database is a compilation of information about the water points collected by the governmental water administration and IMPETUS. The module enables its users to update the database by removing, adding or completing information.

Module 3: Demographic projections

The LISUOC module for demographic projections is a tool that provides and visualizes information on population growth in Central Benin. It was designed to meet the needs of local decision makers and planners, and is based on IMPETUS population projections that have been calculated on a national scale. The module is based on the IMPETUS demographic projections in the scenario Business as Usual, which is described in section II-3.2.

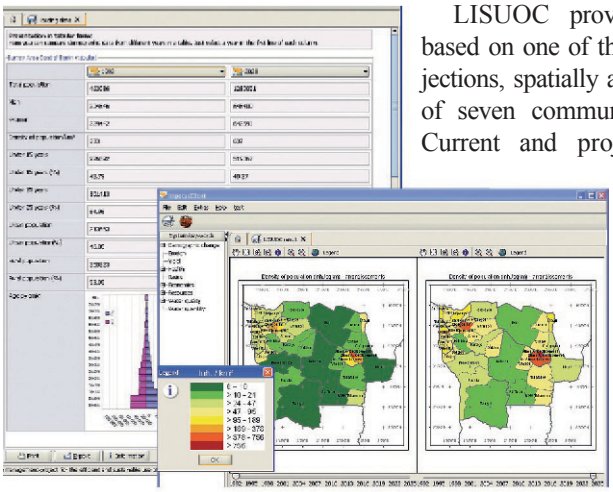

Fig. II-4.4.4: Table with chart and double map panel showing population density per *Arrondissement* from LISUOC Dem.

LISUOC provides demographic data based on one of the central IMPETUS projections, spatially aggregated in the territory of seven communities in Central Benin. Current and projected population data from the census in 1992 and 2002 are also included. The data can be visualized either as a table or as a double map panel (see fig. II-4.4.4) showing the absolute population, the population density or even the age structure of a selected area (Central Benin, communities or districts).

The user can easily choose the mode of visualization and then switch to another mode. A slide bar with a time-scale below the double map panel enables the user to visualize the data for different time periods and to compare current, past and future demographic situations.

II-4.4.5 Conclusions

In conclusion, the problems of Benin's natural resource management are closely related to processes of new policies, decentralization and democratization. The

present analysis of social, political and economic aspects of recent change and their interaction with the environment emphasizes a coexistence of modern and customary land rights, legal pluralism and legal uncertainty. In sum, the decreasing availability of fertile land and water leads to an increase in difficult living conditions.

The highly complex customary land rights and tenure principles prove to be an integral part of the social structure. Customary land rights are implemented by customary authorities and vary from one place to another. At the same time, the national land legislation focuses on land registration as individual property and disregards customary tenure principles. The resulting patchwork of land rights and legal pluralism causes legal uncertainty, contested property claims, tenure insecurity, an uneven distribution of property rights and conflicts over access to land and individualization of land rights.

Furthermore, customary strategies for water management, in the absence of a legal framework, interfere with the development of effective policies. On the local level, actors and institutions compete for political power and influence. Informal actors such as traditional authorities gained in influence with the democratization process. At the same time, officials are formally in charge of natural resource management. The agents of different public services, the officials of the local districts and the decentralized communities have been created in the process of decentralization since the 1990s. The communities hold important legal responsibilities, but they have neither the funds nor the competencies to assume those responsibilities.

Rural water supply infrastructures such as pumps have to be maintained by village committees. Frequently, these committees meet obstacles such as conflicts between members and water users, mismanagement of revenues resulting from the sale of water or malfunctions. Recently, the communities have been in charge of water supply management on the regional level. The implemented system is flexible, but the local population does not really participate in the choice of water management types. No cooperation has been initiated by the communities with international donors. Despite insufficient financial means, the communities lack qualified staff and information such as statistical data. Hence, the IMPETUS information system LISUOC has been developed to provide statistical and qualitative data sets on livelihood strategies, water resources and water management.

References

Bako-Arifari N (1999) Dynamiques et formes de pouvoir politique en milieu rural ouest-africain. Etude comparative sur le Bénin et le Niger. Doctoral thesis, École des hautes études en sciences sociales, Marseille

Degla P (1998) Agrarverfassung in Südbenin: Probleme der Bodenordnung und ihre Auswirkungen auf außerlandwirtschaftliche Erwerbstätigkeit. Cuvillier, Göttingen

Delville P (2000) Harmonising formal law and customary land rights in french-speaking West Africa. In: Toulmin C, Quan J (eds) Evolving land rights, policy and tenure in Africa, pp. 97-101. DFID/IIED/NRI, London

Doevenspeck M, Bako-Arifari N, Singer U (2004) Politique locale et stratégies de mobilisation de ressources financières à l'échelle communale au Bénin. In: Baltissen G, Hilhorst T (eds) Financer la décentralisation rurale: Taxes et impôts à l'échelle locale au Bénin, Burkina Faso et Mali, pp. 16-44. Royal Tropical Institute, Amsterdam

Doevenspeck M (2005) Migration im ländlichen Benin. Sozialgeographische Untersuchungen an einer afrikanischen Frontier. Studien zur Geographischen Entwicklungsforschung. Doctoral thesis, University of Bonn. Verlag für Entwicklungspolitik, Saarbrücken

Food and Agriculture Organisation FAO (2003) Multilingual Thesaurus of Land Tenure, English Version. Ciparisse G. FAO, Rome

Hadjer K (2008) Central Issues of Social and Economic Behaviour in Benin. In: Judex M, Thamm HP (eds) (2008) IMPETUS Atlas Benin: Research results 2000-2007. 3nd edn., pp. 117-118. Department of Geography, University of Bonn, Bonn

Hadjer K (2009) Geschlecht, Magie und Geld. Sozial eingebettete und okkulte Ökonomien in Benin, Westafrika. LIT, Berlin

Heldmann M, Hadjer K, Mulindabigwi V (2008) Land Property Rights in the HVO. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research results 2000-2007. 3rd edn., pp. 121-122. Department of Geography, University of Bonn, Bonn

Le Meur PY (2002) Trajectories Of The Politicisation Of Land Issues. Case Studies From Benin. In: Juul K, Lund C (eds) Negotiating Property in Africa, pp 135-155. Heinemann, Portsmouth

MMEE (Ministère de l'Energie, des Mines et de l'Eau), MDEF (Ministère du Développement de l'Economie et des Finances) (2006) Stratégie pour l'atteinte de la cible 10 de l'objectif n°7 des OMD au Bénin. MMEE and MDEF, Cotonou

Mulindabigwi V (2006) Influence des systemes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin. Cuvillier, Göttingen

Mulindabigwi V, Singer U (2007) Funding municipal budgets in Benin and Rwanda. J Development and Cooperation 34:63-65

Mulindabigwi V, Heldmann M, Hadjer K (2008) Land Use Rights: Migrants and Foreign Cattle Herders. In: Judex M, Thamm HP (eds) (2008) IMPETUS Atlas Benin: Research results 2000-2007. 3rd edn., pp. 123-125. Department of Geography, University of Bonn, Bonn

II-4.5 Vector-borne and water-borne diseases in Benin

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Abstract

Water significantly influences the health of humans. Rainfall is, for example, essential for mosquito breeding and enables the spread of mosquito-borne diseases like malaria in the tropics. Water-borne diseases caused by bacterial and viral contamination of drinking water have a substantial impact on human health. Information systems were developed that (a) assess the impact of Climate Change on malaria risk in Africa and (b) provide information at the village level in the Upper Ouémé catchment on drinking water supply and quality, thus helping to prevent cases of emergency of water-borne diseases.

Keywords: Malaria, mosquito-borne diseases, immunity, malaria modeling, prevalence, seasonality, water-borne diseases, drinking water, water quality, bacterial and viral contamination, latrines, emergency, information systems

II-4.5.1 Introduction

Water influences public health in different aspects. Rainfall, humidity and water availability determine the survival of vectors transmitting infectious diseases to humans. Therefore, changes of these environmental factors alter the prevalence of mosquito-borne diseases in defined geographic regions.

Malaria is one of the most serious health problems in the world (e.g., De Savigny and Binka 2004) and causes about 273 million clinical cases and 1.12 million deaths annually. This life-threatening disease is mostly restricted to young children (e.g., Gupta et al. 1999). At least 90% of the malaria-attributed deaths occur in sub-Saharan Africa (Greenwood et al. 2005). It is well known that a warm and humid climate triggers diseases such as malaria. This vector-borne disease is highly sensitive to global warming and associated changes in precipitation (cp. Confalonieri et al. 2007). A climate-driven pre-existing malaria model has been further developed in IMPETUS and been used for present-day and future malaria projections. Results together with an extensive literature survey are visualized in the MalaRis information system, which might provide helpful information for de-

cision makers in terms of the allocation of resources for improved public health planning and the implementation of control measures.

Besides changes in the environment, water availability is essential for human beings. Drinking water sources can be subject to chemical, microbiological, or viral contamination; hence water quality is a major risk factor for public health. IMPETUS therefore focused on the detection of different viral, bacteriologic, and chemical contaminants in drinking water sources used in rural areas of Benin. Stakeholders and institutions require background information relative to water quality, water hygiene, and options on the prevention of water-borne diseases and measures in case of emergency. Such knowledge is collated in the information system SIQeau.

II-4.5.2 The impact of Climate Change on the risk of malaria in West Africa

Malaria modeling

To assess the observed and future occurrence of malaria in Africa, an existing model from the University of Liverpool was used. The so-called Liverpool Malaria Model (LMM) simulates the spread of malaria at a daily resolution using daily mean temperature and 10-day accumulated precipitation (Hoshen and Morse 2004).

A modification of the model was needed since the original version does not correctly simulate the spread of the malaria disease. Transmission stops too abruptly in the Sahel and far too many mosquito bites are simulated in the equatorial tropics. Numerous model parameters were changed in comparison to the original LMM version. For example, the mosquito survival scheme and sporogonic temperature threshold (16 instead of 18°C), i.e., the minimum temperature for malaria parasite development in the mosquito, were altered. Additionally, various structural changes were introduced into the LMM. For instance, the oviposition of female mosquitoes and the aquatic survival of immature mosquitoes were changed. Unlike the linear approach of Hoshen and Morse (2004), the new LMM version developed in IMPETUS applies a fuzzy distribution model. In this model, mosquito breeding is not possible under completely dry conditions and is reduced under strong rainfall due to the flushing of habitats.

Various sensitivity experiments revealed that the LMM is fairly sensitive to certain model parameters. The proportion of the population that carries the malaria parasite, the so-called prevalence, strongly depends on the applied mosquito survival scheme. At high altitudes, the sporogonic temperature threshold is important. Outside of highland areas, the simulated malaria transmission from mosquitoes to humans is mainly governed by precipitation amounts.

The seasonality of malaria is projected by means of the MARA Seasonality Model (MSM; MARA: Mapping Malaria Risk in Africa project) developed by Tanser et al. (2003). Different temperature and precipitation criteria define the season of malaria transmission. The model uses two monthly and three yearly climate variables.

LMM simulations in West Africa were based on data from 34 synoptic weather stations. This meteorological data set in addition to malaria observations was used for the final tuning of model parameters and the validation of the new LMM version (Ermert 2010). Furthermore, two-dimensional present-day ensemble runs were performed using the LMM on a 0.5° grid for 1960-2000. In this case, the LMM was driven by bias-corrected temperature and precipitation data from the REgional MOdel (REMO; Paeth et al. 2009). In addition, malaria projections were carried out for the period of 2001-2050 according to climate scenarios A1B and B1, in addition to assessment of land use and land cover changes in line with Food and Agriculture Organization (FAO) estimates (see subsect. II-3.2.5).

With regard to the MSM, the REMO ensemble runs for 1960 to 2000 were used for calculation of the present-day climate conditions. The impact of Climate Change on malaria seasonality was assessed for five decades between 2001 and 2050.

Present-day malaria simulations

On the basis of West African weather station data (1973–2006), the LMM shows a decrease in malaria prevalence and duration of the malaria season from stations at the Guinean coast to locations in the northern Sahelian zone (not shown). This is not surprising, since mosquito egg deposition depends on the availability of adequate breeding places. The size of the mosquito population is clearly associated with the strength of the West African summer monsoon precipitation. At the most northern stations in the Sahel, the malaria season either lasts only several weeks or the disease occurs epidemically.

The decline of the malaria prevalence towards the Sahara is also shown by two-dimensional LMM ensemble simulations. In agreement with the annual precipitation amounts, the simulations of the LMM (MSM) show a decrease in malaria prevalence (length of the malaria season) from the Guinea Coast towards the Sahel for the period 1960 to 2000 (see fig. II-4.5.1a and fig. II-4.5.2a,c,e). Malaria transmission is year-round in the equatorial tropics in the area of the largest precipitation amounts, e.g., in southern Cameroon, Gabon, Congo, and Uganda. The regions of epidemic malaria occurrence are identified by large inter-annual variability of the annual malaria maximum prevalence. In West Africa, such areas are located in the Sahelian zone between 13 and 18°N as well as in highland areas (see fig. II-4.5.1c). South of the Sahel and outside of the highland areas, the malaria spread in the simulated population is more stable from year to year and is thus classified as endemic.

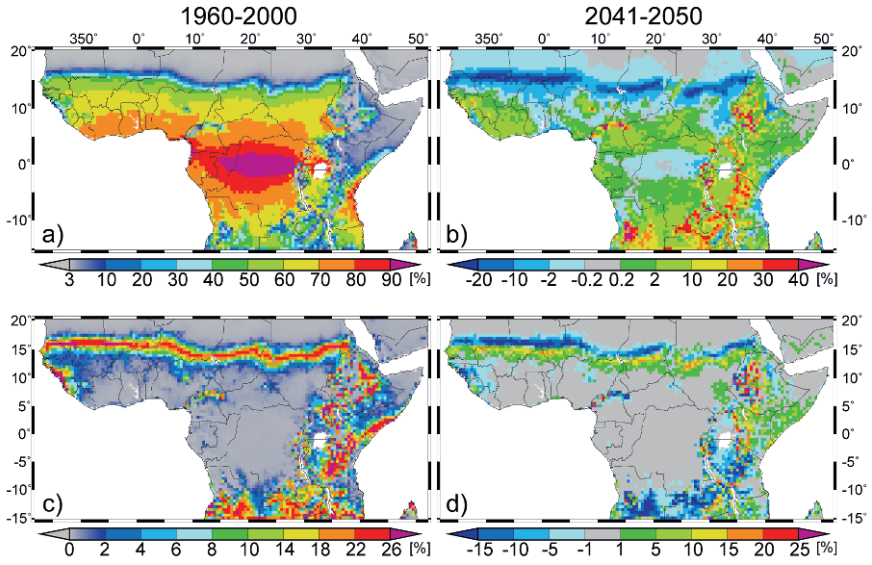

Fig. II-4.5.1: LMM ensemble simulations of: (a) annual average malaria prevalence (in %) and (c) standard deviation of the annual maximum of the malaria prevalence (in %) for 1960 to 2000. (b) and (d) are the same as (a) and (c) but display the differences (in %) between the last decade of the A1B scenario (2041–2050) and the period 1960 to 2000.

Malaria projections (2001-2050)

Largely due to land surface degradation, REMO simulates a prominent surface heating and a significant reduction in the annual rainfall amount over most of tropical Africa in the A1B and B1 climate scenarios (Paeth et al. 2009; see also fig. II-3.2.6.). As a consequence, the malaria projections show a decreased spread of the disease in the Sahelian and Sudanian zone for the decade 2041-2050 (see fig. II-4.5.1b). In addition, the year-to-year variations of the seasonal maximum of malaria prevalence are reduced in the northern part of the Sahel. Therefore, for these areas fewer epidemics or even a malaria retreat from some regions might be expected. However, variability is increasing in the southern part of the Sahelian zone (between 13 and 16°N). As a result, epidemics in these more densely populated areas are becoming more likely as parts of the population will lose their partial immunity against malaria. The maximum of malaria transmission farther south, for example in Benin, remains stable (see fig. II-4.5.1d). However, due to a drier and shorter rainy season the malaria transmission period will be shorter (see fig. II-4.5.2b,d,f).

The reduced precipitation amounts in the REMO climate projections are leading to a decrease in the length of the malaria season in most parts of tropical Africa (see fig. II-4.5.2). In central Burkina Faso and along the coast of Benin,

for example, the start of transmission is retarded from July to August and from April to May, respectively (see fig. II-4.5.2d). In contrast, malaria transmission ceases about one month earlier (see fig. II-4.5.2f). Higher temperatures likewise cause an increase in the season length for highland areas. In West Africa, an extended period of malaria transmission is found for the Fouta Djallon as well as the Adamawa and Jos Plateau (see fig. II-4.5.2b). At the Adamawa Plateau, for example, a five-month longer transmission is found in certain grid boxes due to the temperature increase of about 2°C.

The results regarding the runs for scenarios A1B and B1 are similar to each other. However, as expected the changes are generally stronger in scenario A1B than in B1 and the amplitude of change is most pronounced at the end of the simulation period in the 2040s.

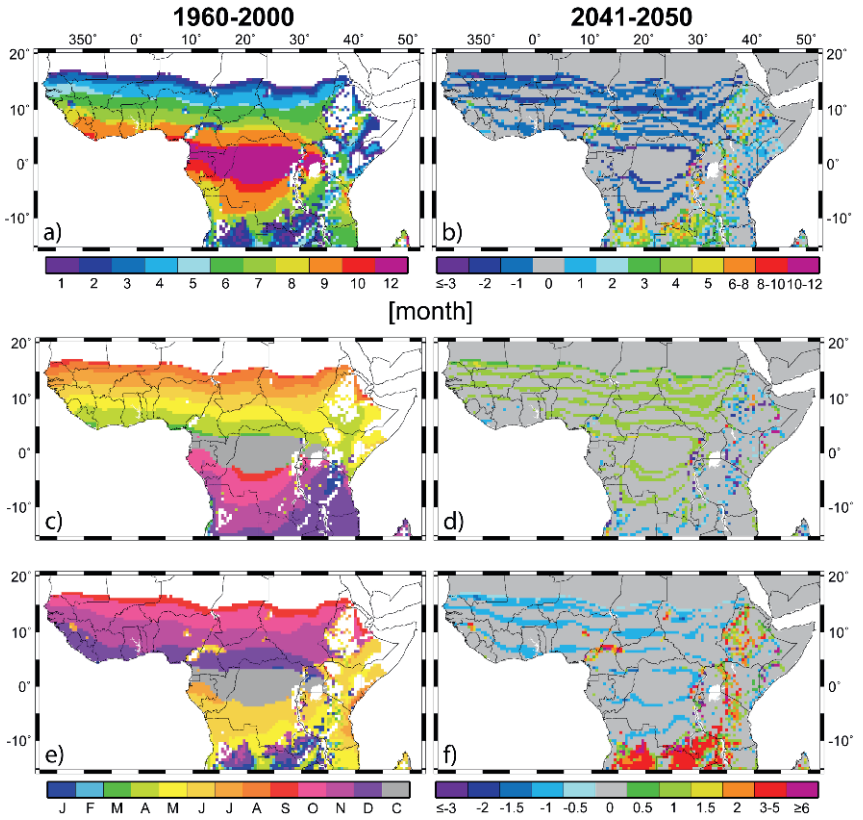

Fig. II-4.5.2: MSM simulations of (a) length (in months), (c) onset, and (e) end of the malaria season for 1960 to 2000. (b), (d), and (f) are the same as (a), (c), and (e) but display the differences (in months) between the last decade of the A1B scenario (2041–2050) and the period 1960 to 2000.

MalaRis Information System

The information system MalaRis ("The impact of Climate Change on Malaria Risk in Africa"; see http://www.impetus.uni-koeln.de/malaris) assesses the malaria risk for Africa under a changed future climate. It provides detailed data on the distribution, seasonality, and variability of malaria transmission. The system further incorporates a rich malaria archive of entomological and parasitological field studies.

II-4.5.3 Water quality in rural areas of Benin

Water quality monitoring

Several chemical, viral, bacteriological, and parasitic contaminants of drinking water sources can be a danger to the consumers. Since the IMPETUS Laboratory of Water Analysis was built in Parakou and started its work in 2002, methods for the detection of viral, bacteriologic, and chemical parameters have been established and applied to investigate the water quality of the rural Upper Ouémé catchment. Furthermore, drinking water sources in the Upper Ouémé catchment were located, documented, classified, and registered (see fig. II-4.5.3). This database of approximate 1,900 water sources serving 105 villages was used to coordinate sample collections in different seasonal settings and to plan further interventions. Due to drying up of wells and construction of new water supplies, the exact amount of water sources varies within the course of the year. The total number of water supplies increased over the intervening years from about 1,300 in 2002 to about 1.900 in 2008.

In the triangle between the cities of Parakou, Bassila, and Djougou, traditional and modern wells are mainly indispensible for the villagers as the water supply; they constitute 90% of all water sources (see fig. II-4.5.4). Closed pump systems represent only 5% of all water supplies in the Upper Ouémé catchment (Mazou et al. 2008). Even though several new pumps have been constructed since 2002, the proportion of the different types of water supplies has remained the same. In several villages, the inhabitants still do not have access to ground water from boreholes at all.

To address the frequency and pattern of viral contamination, samples from drinking water sources in the Upper Ouémé catchment have been taken during the dry and wet season. These water samples were analyzed for the presence of adenoviruses (gastrointestinal as well as respiratory types) as an indicator of viral/fecal contamination, and rotaviruses as an important pathogen of severe diarrhea, especially in small children, in developing countries. Ten liters of water each were collected, transported to the IMPETUS Laboratory and passed through two 1MDS cartridge filters (CUNO filter system, *ZetaPlusRVirosorbR*, 3M Germany) with a flow rate of 5 l/h. The real-time PCR reactions for adenoviruses and rotaviruses were carried out on a Light Cycler (Roche) in Cologne.

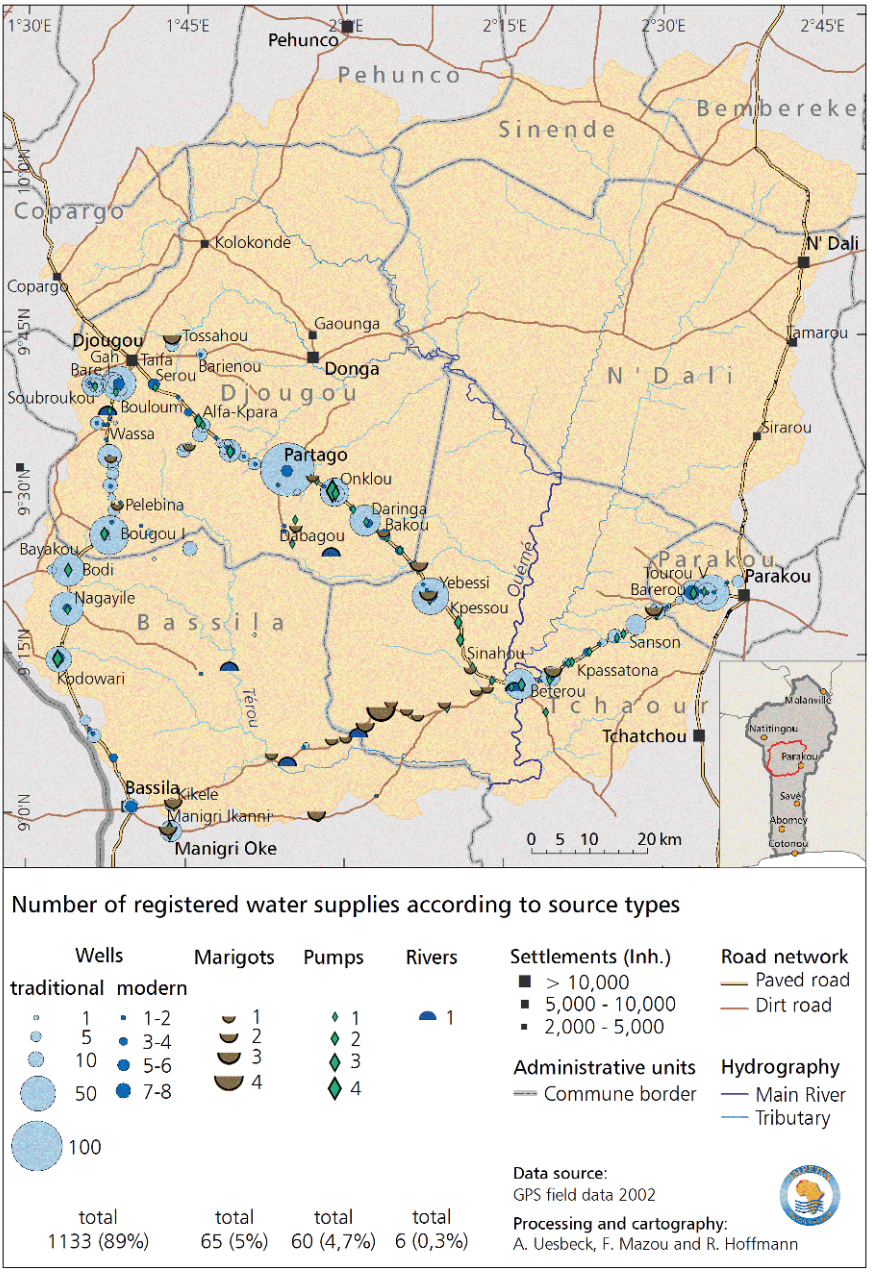

Fig. II-4.5.3: Drinking water sources in the Parakou-Bassila-Djougou triangle.



Traditional well



Modern well



Pump



Surface water

Fig. II-4.5.4: Drinking water sources in rural areas of Benin.

Pathogenic bacteria causing water-borne diseases such as *E. coli*, *Vibrio cholerae*, *Shigella ssp.*, *Yersinia ssp.*, or *Salmonella ssp.* have been isolated from water samples after inoculation of appropriate enrichment broths and growth on selective nutrient agar plates. For identification of organisms, the biochemical properties of suspicious colonies have been determined and finally confirmed at the Institute of Medical Microbiology, Immunology, and Hygiene in Cologne.

Physico-chemical parameters such as the pH, water temperature and water conductivity have been analyzed directly while water sampling in the field with a portable pH/conductimeter.

Viral and bacteriological water quality in drinking water sources

Adenoviruses or rotaviruses were found in 13% of all drinking water sources, and adenoviruses clearly dominated (Verheyen et al. 2009). The dominant detection of adenoviruses might be explained by the great variety of human diseases caused by adenoviruses leading to frequent deposition of this virus in the environment.

Different adenovirus types responsible for respiratory infections were often found in stool samples from children under the age of five hospitalized in Parakou University hospital, together with viruses typically causing diarrheic diseases. Therefore, adenoviruses might also be an appropriate candidate indicator system for viral contamination in environmental samples (Jiang et al. 2001; Godfrey et al. 2005). Overall, the presence of latrines within a 50 m radius of the testing sites was a significant risk factor for viral contamination of pumps and wells (Verheyen et al. 2009). This distance is in agreement with findings obtained during an outbreak of hepatitis A resulting from a leaking sewage tank 60 m apart from water wells (De Serres et al. 1999). It was even speculated that viruses can travel distances greater than 1000 m under optimized conditions (Huang et al. 2000). An improved economic situation in the analyzed rural area led to an increase in the number of latrines, which decreased the risk of human infections by avoiding direct contact with feces. On the other hand, the increase also contributed to the potential viral contamination of surrounding drinking water sources that were nearer than 50 m to the latrines.

Continuous bacteriological drinking water analyses revealed that 70% of all drinking water supplies in the rural Upper Ouémé catchment were contaminated with *Escherichia coli (E. coli)*. *E. coli* lives in the intestinal tracts of humans and other animals and is the principal indicator of fecal pollution of water (Mara 2003; Moe et al. 1991). Disease-causing organisms can be carried in fecal contamination and the detection of *E. coli* in fresh water indicates that pathogens such as *Shigella spp.*, and *Salmonella spp.* may be present as well.

Enteric salmonellae (*S. enterica* subspecies *enterica*) have been isolated from more than 8% of the water sources used by villagers (Uesbeck 2009). Determination of the antigen formula of these strains revealed that they belong to a great variety of different serotypes that rarely cause salmonellosis in European countries. The primary basis for classification of the pathogenic bacterium *S. enterica* is the serotyping scheme of Kauffmann and White in which about 2500 serovars have been recognized according to their flagellin (H-) and lipopolysaccharide (O-) antigens (Grimont and Weill 2007). Two new serotypes of *Salmonella* were detected (*Salmonella* Parakou from a water hole and a second isolate from a stool sample will be named *Salmonella* Kakikoka) and their antigenic formulae were verified by the WHO reference laboratory for *Salmonella* in Paris.

The results of viral and bacteriologic analysis reveal that water from modern and traditional wells that are used as drinking water supplies in most cases do not provide potable water according to World Health Organization (WHO) guidelines (WHO 1997). A very precarious hygienic situation can be observed in most villages. Free running animals, the lack of basic sanitation, uncovered water supplies, and plastic buckets for scooping water that are not stored properly after use may provoke fecal contamination of drinking water.

Photometric analysis revealed that water samples from about 10% of the pumps in the Upper Ouémé catchment are contaminated with nitrates (> 50 mg/l). Drinking water high in nitrates is potentially harmful to infants under six months

of age and can provoke methemoglobinemia, commonly called “blue baby syndrome” (Knobeloch et al. 2000). Proximity to latrines was also found to be one reason of nitrate contamination of water from boreholes. These findings indicate that different aspects have to be considered to improve drinking water quality in rural areas of Africa without general water supply.

Microbiological water quality was much better in pumps than in modern or traditional wells. With very few exceptions (in cases of so called *pompe Vergnet*) water from boreholes with closed pumping systems was not subject to contamination by fecal bacteria. However, viral contamination of 8% of investigated pumps indicates different levels of water quality.

Information system SIQeau

The information system SIQeau (*Système d´Information Qualité de l´eau*) has been developed on the basis of the insights into the situation of drinking water quality and the database providing information of almost all water supplies in the Parakou-Bassila-Djougou triangle. This database was updated in 2008 and enlarged by adding the LISUOC/DGEau database, so that finally SIQeau contains information of about 3,800 water supplies of all seven communes (Parakou, Bassila, Djougou, N´dali, Tchaourou, Ouaké, and Copargo) belonging to the Upper Ouémé catchment.

SIQeau contains basic information about all different aspects of drinking water quality and factors endangering water consumers. Results of water analysis can be requested, and the system highlights hazardous situations at the village level. The user can learn about options for action to ameliorate the situation of drinking water in a certain area. Options like building new pumps, sanitation of old village wells, disinfection of contaminated water supply or alternative systems for storage of water in rural households have been developed on the basis of research results concerning water quality.

SIQeau also provides information about first aid steps and a contact database of responsible persons that should be informed and consulted in case of an outbreak of water-borne infectious diseases. For each village, SIQeau determines the persons in charge and the corresponding contact data. The user can observe the situation of drinking water supply and quality in a certain village or area by choosing several attributes including the types of drinking water source and contamination as well as the depth of the wells. As water supplies from all communes belonging to the Upper Ouémé region have been integrated into the system, the situation in a chosen village or area can be displayed in a GIS map. A hygiene buffer around latrines can be activated to indicate hazards for sources that have a close proximity to latrines.

SIQeau serves as monitoring tool, as data for new water sources can be submitted by the user and those from old water sources that are out of order can be modified or deleted from the database. GPS data and photos can be inserted in addition

to descriptions of the water sources and results of water analysis. The contact database can also be modified in case of changing responsibilities dealing with water quality and infectious diseases.

The continuous updating of all used SIQeau versions shall be observed and delegated by one person in charge of the system, who regularly visits all communes and other users of the database to unify new data and modifications. This person can also be consulted in case of operating difficulties or loss of data.

II-4.5.4 Conclusions

Climate Change affects the living and working conditions of humans and also the likelihood of specific diseases. Public health systems in developing countries are already challenged by the burden of diseases caused by infectious microorganisms. Changes in temperature or rainfall alter the distribution of vectors and the prevalence of diseases. Models like the LMM can help to estimate the burden of the disease in the future with respect to environmental changes. Furthermore, the modeling of different scenarios helps to predict effects under different conditions. Using these results, challenges for public health systems can be standardized and preparations can be planned. It is in the nature of information systems that they are less useful for the far future but help to provide reliable data in a current situation and help to plan interventions in the near future. Additionally, in the IMPETUS laboratory in Parakou, different methods to monitor water quality have been set up and are now applicable by trained persons. A major impact of the IMPETUS project is that water quality can be addressed in more detail in Parakou and surrounding areas. Overall, different data sets were implemented that can help to improve the public health system in these areas.

References

Confalonieri U, Menne B, Akhtar R, Ebi KL, Hauengue M, Kovats RS, Revich B, Woodward A (2007) Human health. In: IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 391-431. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press, Cambridge, UK

De Savigny D, Binka F (2004) Monitoring future impact on malaria burden in sub-Saharan Africa. Am J Trop Med Hyg 71(2):224-231

De Serres G, Cromeans TL, Levesque B, Brassard N, Barthe C, Dionne M, Prud'homme H, Paradis D, Shapiro CN, Nainan OV, Margolis HS (1999) Molecular confirmation of hepatitis A virus from well water: epidemiology and public health implications. J Infect Dis 179:37-43

Ermert V (2010) Risk assessment with regard to the occurrence of malaria in Africa under the influence of observed and projected climate change. Doctoral thesis, University of Cologne, Cologne

Godfrey S, Timo F, Smith M (2005) Relationship between rainfall and mi-crobiological contamination of shallow groundwater in Northern Mozambique. Water SA 31:609-614

Greenwood BM, Bojang K, Whitty CJM, Targett GAT (2005) Malaria. Lancet 365:1487-1498

Grimont PAD, Weill FX (2007) Antigenic formulae of the Salmonella serovars 9th edn. World Health Organisation, Collaborating Centre for Reference and Research on Salmonella, Paris. http://www.pasteur.fr/sante/clre/cadrecnr/salmoms/WKLM_2007.pdf. Accessed 02 December 2009

Gupta S, Snow RW, Donnelly CA, Marsh K, Newbold C (1999) Immunity to non-cerebral severe malaria is acquired after one or two infections. Nat Med 5:340-343

Hoshen MB, Morse AP (2004) A weather-driven model of malaria transmission. Malaria J 3:32

Huang PW, Laborde D, Land VR, Matson DO, Smith AW, Jiang X (2000) Concentration and detection of caliciviruses in water samples by reverse transcription-PCR. Appl Environ Microb 66:4383-4388

Jiang S, Noble N, Chu W (2001) Human adenoviruses and coliphages in urban runoff-impacted coastal waters of Southern California. Appl Environ Microb 67:179-184

Knobeloch L, Salna B, Hogan A, Postle J, Anderson H (2000) Blue babies and nitrate-contaminated well water. Environ Health Persp 108:675-678

Mara D (2003) Faecal indicator organisms. In: Mara D, Horan N (2003) The Handbook of Water and Wastewater Microbiology, pp. 105-113. Elsevier, San Diego, CA

Mazou F, Uesbeck A, Baginski R (2008) Drinking water supply in the Upper Ouémé Catchment. In: Judex M, Thamm H-P (eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn., pp. 45-46. Department of Geography, University of Bonn, Bonn

Moe CL, Sobsey MD, Samsa GP, Mesolo V (1991) Bacterial indicators of risk of diarrhoeal disease from drinking-water in the Philippines. B World Health Organ 69:305-317

Paeth H, Born K, Girmes R, Podzun R, Jacob D (2009) Regional Climate Change in Tropical and Northern Africa due to Greenhouse Forcing and Land Use Changes. J Climate 22:114-132

Tanser FC, Sharp B, le Sueur D (2003) Potential effect of climate change on malaria transmission in Africa. Lancet 362 :1792–1798

Uesbeck A (2009) Isolierung und Typisierung von Salmonellen aus Trinkwasserquellen in Benin, Westafrika. Doctoral thesis, University of Cologne, Cologne

Verheyen J, Timmen-Wego M, Laudien R, Boussaad I, Sen S, Koc A, Uesbeck A, Mazou F, Pfister H (2009) Detection of adenoviruses and rotaviruses in drinking water sources used in rural areas of Benin, West Africa. Appl Environ Microb 75:2798-2801

WHO (1997) Guidelines for drinking-water quality. Vol. 3, Surveillance and control of community supplies. WHO, Geneva. http://www.who.int/water_sanitation_health/dwq/gdwqvol32ed.pdf. Accessed 02 December 2009





5 Impacts of Global Change in Southern Morocco

5.1 Importance of resource management for livelihood security under Climate Change in Southern Morocco

5.2 Impacts of Global Change on water resources and soil salinity in Southern Morocco

5.3 Land use and land cover in Southern Morocco: Managing unpredictable resources and extreme events

5.4 Migration and resource management in the Drâa Valley, Southern Morocco

II-5 Impacts of Global Change in Southern Morocco

B. Reichert

Coping with the impacts of Global Change is a major challenge for the vulnerable semi-arid to arid Drâa catchment, as well as for Southern Morocco as a whole, because of its already dry conditions and limited water availability. People rely on water not only for drinking, but also to secure their livelihood by irrigation for subsistence or cash crop farming, live stock production, small enterprises, and tourism. Other environmental issues pertinent to the area include land degradation by overgrazing, soil and water salinization due to intensive irrigation agriculture and depletion of the groundwater reservoirs by overuse of groundwater for irrigation purposes. This chapter highlights examples of the ways in which Global Change may affect the future of the Drâa catchment.

In section II-5.1 the importance of proper resource (both water and land) management as it relates to livelihood security is tackled. The main income-generating activities in the region are agriculture, which is heavily dependent on water availability, and livestock husbandry, which relies on land and vegetation productivity. Agronomic and economic options for irrigation water management are analyzed and simulated for the IMPETUS climate scenarios with a hydro-economic simulation model. Special emphasis is given to the development of farm income, taking into account water scarcity, groundwater overuse and irrigation-induced salinization of soil and water. Examples of intervention possibilities, like the implementation of groundwater charges, clearly show how policy might be able to cope with the effects of Climate Change. A sound analysis of the resource management strategies for the rangeland demonstrates the capability of the transhumant pastoralists to cope with the existing variability of fodder resources on local pastures. Simulations of the vegetation dynamics in relation to grazing activities with an ecological model for climate scenarios help to illustrate the resilience of the vegetation to grazing impacts.

The focus of the second section II-5.2 is the availability of water in the Drâa catchment in the future scenarios. Using a number of adapted, calibrated and validated models transferred in management tools, a general decline in surface water availability, but no particular trend for extreme periods with scenario calculations is demonstrated. Snow coverage in the High Atlas will decrease in the future due to an increase in air temperature. The analyses, therefore, show a likely decrease in surface runoff in the Upper Drâa valley. Reduced surface water availability will increase the pressure on the groundwater resources downstream of the reservoir Mansour Eddahbi, as demand for irrigation water is high. Both climate and socio-economic scenarios reveal significant effects on water resources. Due to limited freshwater from the reservoir, soil and groundwater salinity will increase

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in the future, eventually causing the failure of food production if no appropriate measures are undertaken. Furthermore, the problematic of the different downscaling methodologies for the various regional climate model outputs are highlighted.

In section II-5.3, land use management options in the High Atlas region under the impact of extreme climate events are described. It focus is on pastoral land, where key traits are identified that mitigate the negative effects of extreme weather events (droughts and floods). Local land use mitigates drought effects through preventive natural resource management, such as herd management, and access to alternative resources. This adaptive land management ensures the availability as well as the resilience of pastoral land and increases the capacity of rangeland vegetation to buffer rainfall variability. Using a soil erosion model, the current and future risk for soil erosion by water is demonstrated. Climate scenario calculations show that accelerated erosion will occur due to a reduced protective vegetation cover and a projected increase in extreme daily rainfall in the High Atlas Mountains. Depending on the combination of different climate and socio-economic scenarios, the negative effect could become either more or less severe.

In the last section II-5.4, an overview of local social structures that govern processes of decision making related to natural resource management in Southern Morocco is provided. Focus is given to processes of socio-economic and demographic change in the Drâa catchment directly influenced by water availability on both the regional and local scales. In this context, patterns of migration, as well as ethnic affiliations, social status of individuals or groups and their effects on economic strategies, are analyzed. Labor migration is a common strategy to locally secure livelihoods of the rural population, leading to relatively low population growth in the rural areas and increasing urbanization.

II-5.1 Importance of resource management for livelihood security under Climate Change in Southern Morocco

A. Kuhn, C. Heidecke, A. Roth, H. Goldbach, J. Burkhardt, A. Linstädter, B. Kemmerling, and T. Gaiser

Abstract

The income-generating activities in the Middle Drâa valley are strongly based on water use and land resources. Nevertheless, labor migration and tourism increasingly help to diversify the sources of income for farm and pastoral households. The most important component of water demand in the Drâa basin is crop production in the oases of the Middle Drâa valley, which would be impossible without the extensive use of irrigation schemes. Agronomic and economic options for irrigation water management are analyzed and simulated. From an agronomic perspective, specific emphasis is put on problems of temporal water scarcity and on problems with increasing salinization of soils as a consequence of irrigation water use and groundwater mining. Using a hydro-economic simulation model, the consequences of long-term trends in the volatility of water supply are simulated. Land use, by contrast, is dominated by extensive pastoral-nomadic production. The physical biomass productivity of extensive pasture under Climate Change is simulated using a locally adapted version of the SAVANNA-Model. This spatially explicit, process-orientated model simulates spatial animal dynamics based on the distribution of biomass productivity. In addition, we look into the resilience mechanisms of pastoral-nomadic range management in the wider Drâa region. Pastoralists' mobility in the region allows for the use of and creates reliable fodder resources, which are ecological buffers against environmental variability. Decisions also depend on socioeconomic resources and individual networks, which function as economic buffers.

Keywords: Livelihood security, irrigated agriculture, transhumance, crop yield response, water pricing

II-5.1.1 Introduction

The arid zone of the Drâa valley, extending from the slope of the High Atlas Mountains to the northern border of the Sahara desert, is characterized by scarcity and heterogeneity of water supply, which limits income created by agriculture. Rangeland areas are used by pastoralists (nomads and sedentary farmers), whereas arable and irrigated (traditional) agriculture is found in the oases. The model-based projections for Morocco discussed in section II-3.2 suggest significant drying, implying a greater shortage of water in the region in the future. Both traditional and modern approaches to resource management are faced with the challenge to secure the incomes of a growing population that depends on land and water resources without compromising the natural resource base.

This section focuses on income-generating activities that are heavily based on the use of water and land resources. The most important component of water demand in the Drâa basin is crop production in the oases of the Middle Drâa valley, which would be impossible without the extensive use of irrigation schemes. Agronomic and economic options for irrigation water management are analyzed and simulated. From an agronomic perspective, specific emphasis is put on problems of temporal water scarcity and on problems with increasing salinization of soils as a consequence of irrigation water use and groundwater mining. Using a hydro-economic simulation model, the consequences of long-term trends in the volatility of water supply are simulated. Land use, by contrast, is dominated by extensive pastoral-nomadic production. We look into resilience mechanisms of the pastoral-nomadic range management in the wider Drâa region. Pastoralists' mobility in the region makes use of and creates reliable fodder resources, which are ecological buffers for environmental variability. Decisions also depend on socioeconomic resources and individual networks, which function as economic buffers. In addition, the physical biomass productivity of extensive pasture under Climate Change is simulated using a locally adapted version of the SAVANNA-Model. This spatially explicit, process-orientated model simulates spatial dynamics of animal herds based on the distribution of biomass productivity.

II-5.1.2 Crop management in oasis agriculture in the Drâa basin

In the south of Morocco, crop production is carried out in irrigation-based oasis systems. With respect to the water availability and the thermal and pedogenic conditions, two different types of oases agricultures can be distinguished: (1) The mountain oases, with a virtually permanent supply of high quality surface water, but with lower annual mean temperatures and soils with predominantly high coarse fragment content and (2) the desert oases with a limited and controlled supply of high quality surface water from the Mansour Eddahbi dam and ground water with

variable quality as a complementary water source. In desert oases, the annual mean temperatures are considerably higher, and the soils generally contain less coarse fragments.

Crop management in the desert oases of the Drâa valley

Agricultural production is a major activity in the desert oases, both for food security and for income supplementation. As crop production strongly depends on irrigation, water scarcity is a primary problem. During years of drought or insufficient filling of the dam, farmers suffer from a lower and more unreliable supply of water from the releases of the Mansour Eddahbi reservoir. Farmers must then substitute good quality surface water from the dam with more costly groundwater. Groundwater, however, has variable salt content, which leads to decreasing crop yields in the long term.

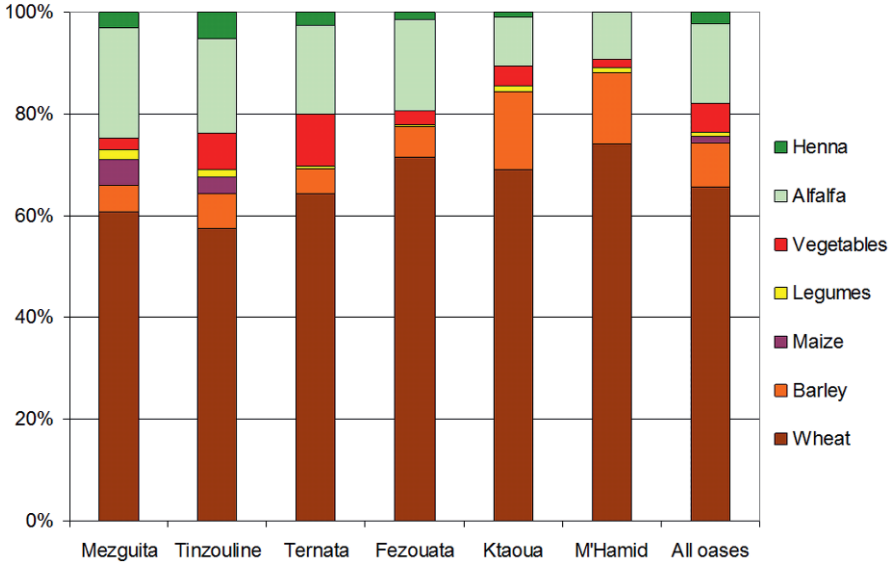

Fig. II-5.1.1: Major crops (except date palms) in the Drâa oases in the season 1996/97 (Source: MADRPM 2000).

In terms of ground coverage, wheat is the dominant annual crop in the desert oases, covering 58 to 74% (see fig. II 5.1.1) of the cultivated area. Depending on the oasis, alfalfa and barley rank just below wheat. All other crops have less than 10% coverage on the cropland, with the exception of the oasis Ternata, where vegetable production covers slightly more than 10% of total crop area.

The production of dates, the most economically important agricultural activity, is typically carried out on the border lines of irrigation channels and irrigated fields. Because field sizes are small, a considerable number of palm trees are recorded in the oases. Transpiration measurements have been conducted on date palms, and such measurements show that the trees consume about 700 mm of water per year. With an average yield of 657 kg ha^{-1}, the water use efficiency of well-watered date palms is around 0.094 kg m^{-3}. The annual water consumption of date palms is extremely high compared to the natural vegetation (*Artemisia* shrubs), which transpires an average of 12 mm per year. Hence, the water consumption of one hectare of date palms is equal to 60 hectares of natural vegetation (IMPETUS 2006). In both cases, insufficient water supply leads to a reduction in transpiration of 60 to 70%. In the case of the date palms, this leads to increased mortality, whereas the natural vegetation reacts by reducing individual biomass while maintaining the population density (IMPETUS 2006). Another serious constraint on date production is a fungus (*Fusarium oxysporum* sp. *Albedinis*), called *Bayoud* in the local language. In the initial stage of the disease, the fungus causes drying and bleaching of palm leaves; over time, it can devastate entire plantations. Traditionally, infected trees are burned. Research to develop new resistant varieties with high quality fruits is underway (Fernandez et al. 1995).

Under the prevailing temperature conditions in the desert oases, wheat, the major annual crop, is expected to yield 5 to 6 Mg ha^{-1} under optimum water and

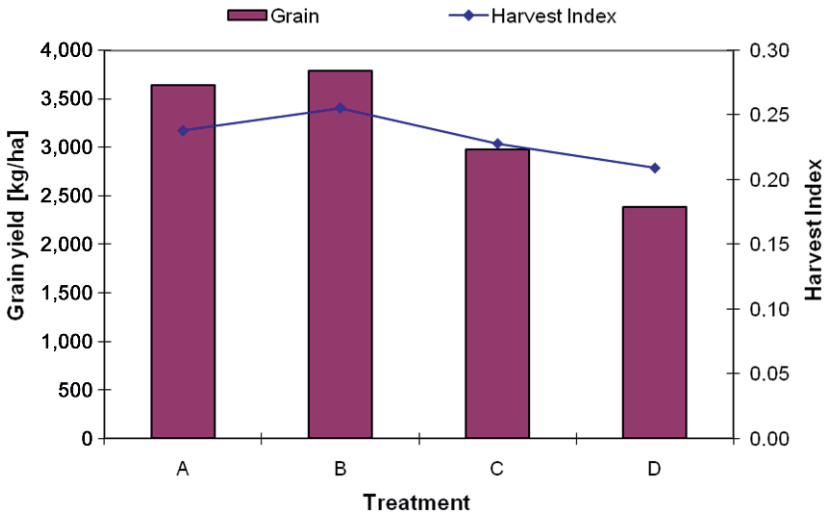

Fig. II-5.1.2: Mean grain yield and harvest index (ratio between grain yield and total above-ground dry matter) from a four year field experiment at Zagora comparing four treatments with different irrigation volumes and application dates (A: 280 mm, no irrigation at end of flowering, B: 280 mm, no irrigation at shooting, C: 210 mm, no irrigation at shooting and panicle appearance, D: 280 mm, no irrigation at panicle appearance and end of flowering) (Source: Kourdi 1996).

nutrient supply levels.[1] However, in contrast to barley and date palms, wheat is more sensitive to high electrical conductivity in the soil, and its productivity increasingly suffers from salt stress in the southern oases. When electrical conductivity of the soil is below 4 dS m^{-1}, the major constraint to high crop yields is water (FAO 1979). Field experiments at the research station of ORMVAO at Zagora indicate that wheat yields of almost 4 Mg ha^{-1} can be achieved with four water applications of 70 mm when the timing is optimal, i.e., water is applied at panicle appearance and at the end of flowering (see fig. II 5.1.2). These two application dates guarantee a sufficient water supply during critical stages of flowering and grain filling. In this case, the highest grain yields and harvest index are achieved. When additional precipitation is taken into account, the water use efficiency of wheat production is between 0.71 kg wheat m^{-3} (Treatment A) to 0.85 kg wheat m^{-3} (Treatment B). Nevertheless, the dry matter partitioning between shoot and grains appears to be inadequate, expressed by harvest indices between 0.18 and 0.28. This may indicate either a sub-optimal water supply (i.e., the overall amount of 280 mm and the application frequency of four applications over the cropping season may be too low) or sub-optimal nutrient availability.

If water supply is sufficient and soil salinity is at an acceptable level, nutrients are the second constraint on optimum wheat production, as shown by the response of wheat to fertilizer application (see fig. II 5.1.3). In a farm survey with 81 farms, it has been observed that the application of combined NPK (a mixed fertilizer con-

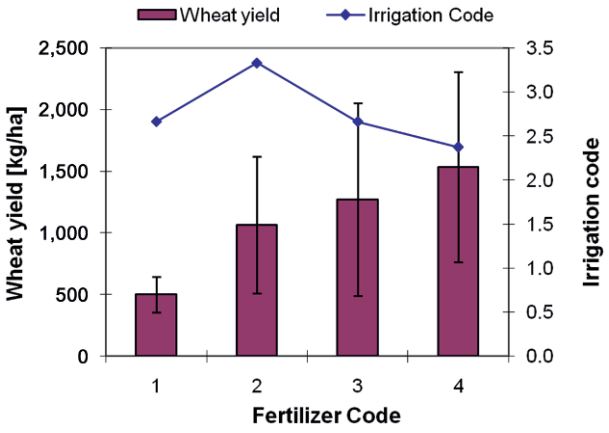

Fig. II-5.1.3: Mean wheat yield in relation to fertilizer application and irrigation rate from a sample of 47 farms (fertilizer code signifies ranges of NPK and ammonium sulfate application rates of (1) 17-100 kg ha^{-1} (2) 101-200 kg ha^{-1} (3) 301-600 kg ha^{-1} and (4) 601-1000 kg ha^{-1}; irrigation code signifies rate of water application per cropping period in hours per hectare: (1) 1-50 h ha^{-1} (2) 51-100 h ha^{-1} (3) 101-300 h ha^{-1} (4) 300-600 h ha^{-1}).

[1] Mg stands for megagram = 1 x 10^6 grams or a metric ton.

taining 14% of nitrogen, 23% of phosphorus, and 11% of potassium) and ammonium sulfate mineral fertilizer at rates between 600 and 1,000 kg ha^{-1} almost tripled wheat yield compared to rates of 17 to 100 kg ha^{-1}, although yield variability is considerable due to the interactions between water and nutrients. The irrigation rates were similar at all four fertilization levels, but were relatively small, because the survey was carried out in a year in which the dam capacity to provide irrigation water was low.

Agricultural production in the mountain oases

Cropping systems in the mountain oases are quite different from those in the desert oases. This is due to the lower temperatures and shorter vegetation periods, which, depending on the altitude, allow only one crop per season. Below 2,500 m, however, it is possible to plant two crops per year, the first cycle being from March to July and the second cycle from July to November. In the first season, barley is the dominant annual crop, because it has the shortest growing cycle and is therefore a prerequisite if a farmer wants to harvest a second crop in the same year (see fig. II 5.1.4). Thus, in the second season, not all areas that had been cropped in the first season can be cultivated. Maize and vegetables are the dominant annual crops in the second season.

Due to the abundance of water from springs and the permanently flowing river, irrigation volumes total up to 2,300 mm per crop (IMPETUS 2006). If the

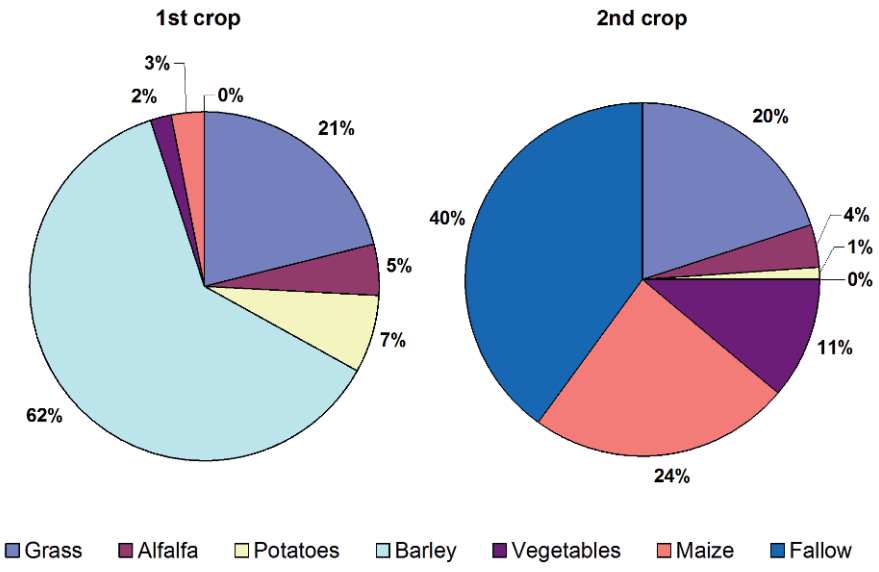

Fig. II-5.1.4: Percentage of main crops during the first and second cultivation cycle at Tichki (2,300 m asl) (Source: Kirscht 2008).

irrigated volumes are compared to the yields of barley (3,000 to 6,000 kg ha-1) and maize (800 to 3,000 kg ha-1), the calculated water use efficiency is in the range of 0.17 to 0.12 kg m-3. This is roughly a fifth of the water use efficiency of wheat found at the research station in the Middle Drâa valley (see values for wheat above), where a maximum of 420 mm was applied per crop. It is apparent that the farmers in the mountain oases apply water excessively, and most of the applied water drains unproductively beyond the root zone.

II-5.1.3 Assessment of economic effects of Climate Change in the Middle Drâa oases using the MIVAD model

While crop production provides additional food and income for the local population in the Drâa basin, it is also the largest consumer of water, for the purpose of irrigation. The aim of this subsection is to assess the impact of Climate Change, and hence changing water availability, on water use for irrigation and other farm-based activities for income generation in the six Drâa oases (Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua, M'hamid). Therefore, applications of MIVAD (*Modèle Integrée du Vallée du Drâa*) simulation model – described in more detail in subsection I-8.2.2 of this book – for recursive-dynamic simulations are outlined first, followed by a selection of modeling results that focus on the impact of Climate Change and intervention possibilities.

Climate Change scenarios using the MIVAD modeling approach

To simulate the impact of Climate Change on water use, the MIVAD model is modified to include the dynamically downscaled IPCC Climate Change scenarios A1B and B1 using the REMO model (see sect. II-3.2.5). Recursive-dynamic simulations with MIVAD are carried out for the years 2000-2020, which is the time frame of the national development strategy of Morocco. The simulations include aspects of population growth within this time period, which means that demand for drinking water in the Drâa valley will exogenously increase over the simulation period at a rate of 3.1% annually for urban and 0.8% annually for rural areas, following the results of Penitsch et al. (2005). Water releases from the reservoir into the Middle Drâa river basin are decided on an annual basis and are not managed over a multi-annual horizon, while simultaneous simulations are made on an annual basis.

Climate Change scenarios are introduced into the MIVAD model by transforming the rainfall of the IMPETUS climate projections into scenarios of inflows into the Mansour Eddahbi reservoir by regression analysis. This is possible, as rainfall data and inflows are highly correlated (Schulz et al. 2008). Both the record of historical inflows from 1972 (the year the reservoir was put into operation) until 2000, as well as the estimated inflow scenarios on the basis of the IMPETUS climate

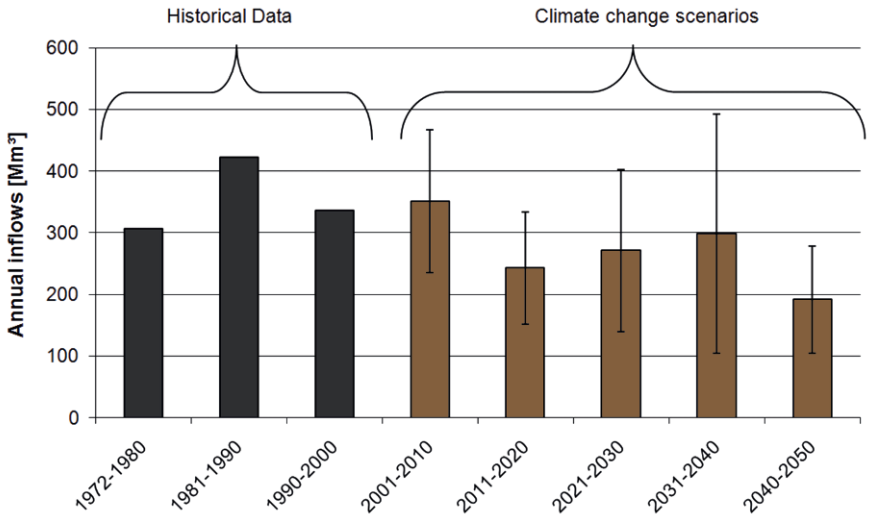

Fig. II-5.1.5: Observed and predicted inflows into the reservoir across all decades from 1972 to 2050 (Source: IMPETUS climate and hydrological scenarios, own calculations).

scenarios A1B and B1 in figure II 5.1.5, suggest that inflows are likely to decrease in the future. The black line in the bar diagram shows the standard deviation calculated from Climate Change scenarios for three ensemble runs for the scenarios of A1B and B1, numbered 911-913 (A1B) and 921-923 (B1). It can be stated that inflows are likely to decrease, although this interpretation has to be considered cautiously as there is substantial variation between ensemble runs.

The inflows into the Mansour Eddahbi reservoir are an exogenous variable in the MIVAD model and constitute a decisive factor for the model results, as they determine the major part of the water availability in the system. Lateral inflows and groundwater aquifers also contribute to water availability. However, most groundwater is extracted from the shallow aquifers below the riverbed, groundwater availability. Thus, it is directly dependent on the amount of reservoir inflows due to infiltration of water from the riverbed and infiltration from irrigation water on the fields (compare also groundwater balance as described in subsection I-8.2.2).

Impact of Climate Change on modeling results

The following results are based on averages of simulations of historical inflow data from the years 1972 until 2000, and an average of recursive dynamic results for the two IPCC scenarios from 2000 until 2020. Furthermore, an alternative water distribution is discussed as an intervention scenario, and water pricing as one option for groundwater resource preservation is examined.

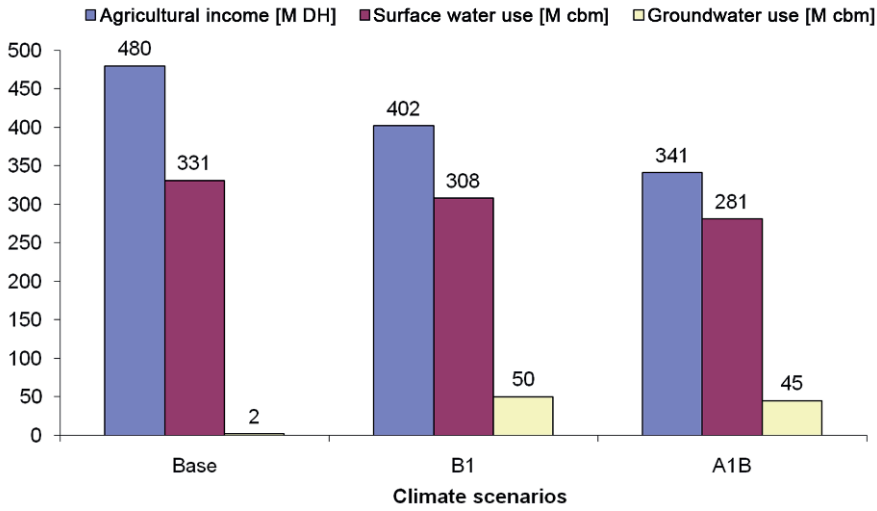

Fig. II-5.1.6: Development of agricultural income, surface water (SW) and groundwater (GW) use: comparison of base line (averages from 1972 to 2000) to B1 and A1B scenarios (calculated from 2000 to 2020) (Source: calculation with the MIVAD model in 2009). Results of the climate change scenarios represent one ensemble run for each scenario (912 and 922) from 2000 until 2020. The base scenario refers to an average of inflows from 1972 until 2000.

Figure II 5.1.6 summarizes the impact of Climate Change until 2020 on water use and farm income. It is obvious that farm income is likely to decline in the future as a result of lower water availability in the Mansour Eddahbi reservoir. The decreasing water availability is also reflected in the agricultural surface water use, which represents the water drawn from the Drâa river for agricultural irrigation. Consequently, groundwater use is likely to increase nearly twofold depending on the underlying Climate Change scenario. As IPCC A1B represents a stronger greenhouse-gas climate forcing and therefore a stronger projected rainfall decline, water availability is the lowest in this scenario, and model results are the most drastic under this scenario as well.

Results of figure II 5.1.6 underline the importance of water management measures to assure more sustainable water use in the future. Two intervention possibilities shall be discussed here. In the first, simulations are made for an alternative water distribution strategy for surface water that is provided by reservoir releases through the Drâa river. In the second simulation, groundwater pricing is discussed as one option for groundwater resource preservation.

Currently, water is distributed quite evenly among the six oases. In the MIVAD model, this is represented by a share of surface water granted to each oasis depending on the amount of arable land of this oasis and its water requirements, which depend on the crops cultivated. If no explicit water distribution rule is applied to water allocation among oases, MIVAD allocates surface water according to the principle of maximization of basin-wide income, which is why this form of

Table II-5.1.1: Agricultural income under alternative water distribution rules (in million Moroccan Dirham) in the six oases (A1 to A6) (Source: MIVAD model simulations 2009). Note: The scenario assumed is the A1B climate change scenario (run 912) of the IMPETUS project, which has been transformed into reservoir inflows.

	Area distribution	Optimal
Mezguita (A1)	47.3	51.4
Tinzouline (A2)	54.8	57.3
Ternata (A3)	96.9	102.0
Fezouata (A4)	47.5	50.0
Ktaoua (A5)	68.3	70.2
Mhamid (A6)	26.6	28.9
Average	56.9	60.0
Standard deviation	23.8	24.6

water distribution is called the 'optimal' water distribution. Applying area-based water distribution rules leads to a more even distribution of water and farm incomes among the oases as compared to the 'optimal' distribution (see table II-5.1.1).

Another option is the implementation of groundwater charges to stabilize groundwater use. The problem of water pricing in other river basins in Morocco has been discussed by Tsur et al. (2004), who states that water charges are levied in all other Moroccan river basins; however, such charges often do not cover the cost of operation and maintenance of the irrigation schemes. Heidecke et al. (2008) conclude for the Middle Drâa basin that groundwater pricing is a favorable option in long periods of drought, as groundwater is preserved until surface water is scarce. However, this analysis does not include aspects of groundwater salinity and Climate Change. Thus, in the following simulations, groundwater charge and its impact on groundwater tables and farm income are both evaluated under the assumptions of Climate Change scenario A1B. Figure II 5.1.7 depicts the fill levels of the aquifers in meters. In the simulations with no charge, groundwater use is still more expensive than surface water due to the running costs of the motor pumps. Nevertheless, with an additional charge of 40 Moroccan cents, groundwater use is even less attractive than surface water and only used for irrigation if surface water is scarce and groundwater use is economically efficient. Consequently, farmers use less groundwater for irrigation than in the case with no charges, and groundwater levels are therefore more stable over the years.

This higher stability of groundwater levels over the years has a direct effect on farm income in the six oases. Figure II 5.1.8 displays farm income over the 20 year horizon for the six oases, from north to south along the Drâa river. It can be seen that in the long run, a groundwater charge leads to more stable farm incomes.

The effect of a groundwater charge on groundwater use and income is summarized in table II 5.1.2. The implementation of a groundwater charge induces a lower level of groundwater use, presented as the average over 20 years. Surprisingly, agricultural income is also slightly higher than with no extra charge, although the

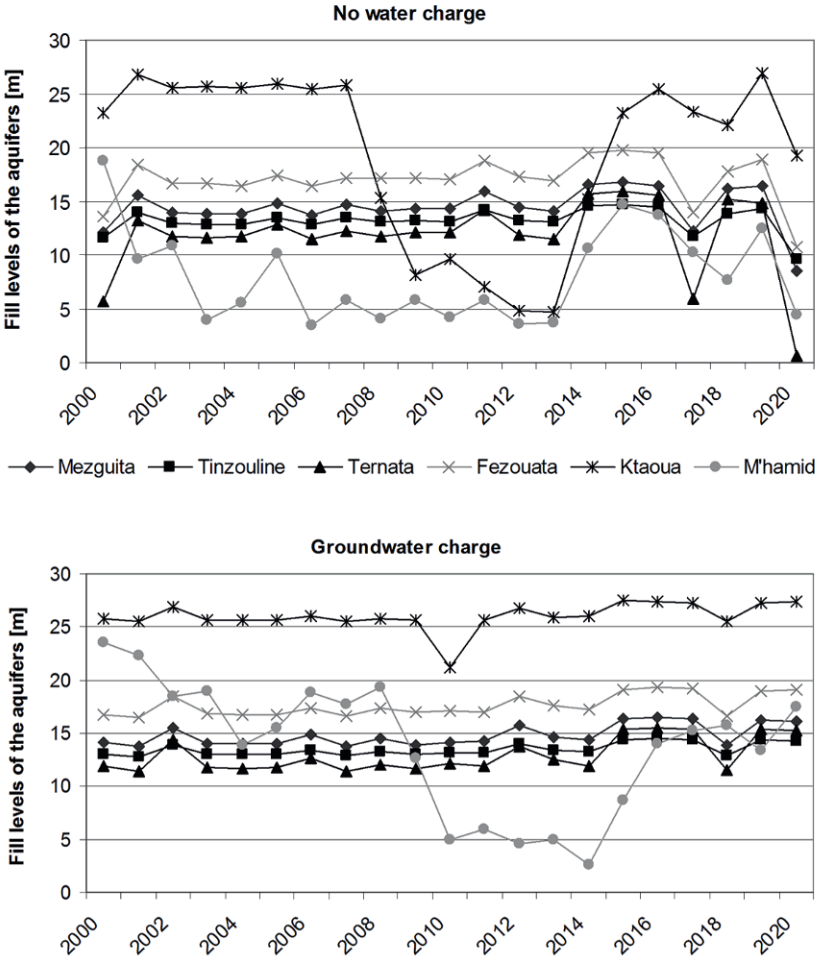

Fig. II-5.1.7: Fill levels of the six aquifers (GW1 to GW6) of the six oases in the Middle Drâa valley (depth of water table in meter [m]). Source: MIVAD model simulations 2009. Note: The scenario assumed is the A1B climate change scenario (run 912) of the IMPETUS project which has been transformed into reservoir inflows.

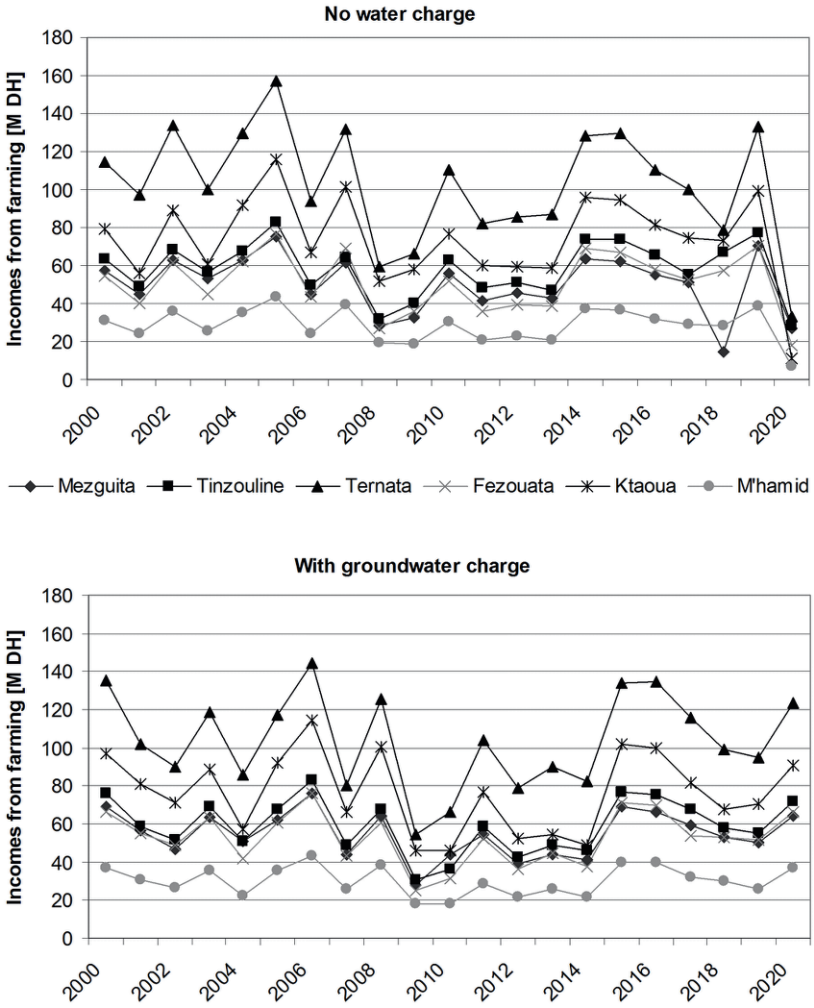

Fig. II-5.1.8: Development of agricultural income in the six oases (A1 to A6) of the Middle Drâa valley in million Moroccan Dirham [MDH] (Source: MIVAD model simulations 2009). Note: The scenario assumed is the A1B climate change scenario (run 912) of the IMPETUS project, which has been transformed into reservoir inflows.

Table II-5.1.2: Impact of a groundwater charge in contrast to no charges (average of 20 years assuming climate change scenario A1B) (Source: MIVAD model simulations 2009).

	A1B	
	No charge	**Groundwater charge**
Agricultural river water use [Mm³]	280.50	303.70
Agricultural groundwater use [Mm³]	44.60	25.60
Agricultural income basin-wide [M DH]	341.40	351.30
Shadow agricultural water price [DH/m³]	1.79	1.76

farmers incur extra costs for using irrigation water. This cost is due to the more stable groundwater availability over the 20 year time span, which then leads to a more stable income. The greater stability of water availability is also presented in the lower shadow price for irrigation water, which can be interpreted as a factor representing the scarcity of irrigation water.

Discussion

The simulations provide an overview on policy alternatives with an integrated economic and hydrologic modeling tool for water management. The MIVAD model is applied to simulate the impact of the Climate Change scenarios by IPCC and IMPETUS on irrigation agriculture in the Drâa valley. Furthermore, two intervention scenarios have been presented. Depending on the objectives of stakeholders for water management in the Middle Drâa valley, the different policy options need to be evaluated carefully. An optimal water distribution rule might lead to higher overall farm income, but, when evaluating on equity and poverty aspects, the current practice is preferable. A groundwater charge leads to more sustainable groundwater tables in the long run, but administrative costs have not been discussed here, and the implementation of a groundwater charge might not be feasible from an administrative point of view, even without taking the short term effects on farm incomes into account.

II 5.1.4 Pastoralists' resource management and livelihood security in the Drâa region

While cropping in the Drâa valley is dependent on the availability of large amounts of irrigation water, transhumant livestock husbandry, as the second important resource-based production mode, rests on the vast rangelands characterizing the region. In this subsection, we analyze the resource management strategies of transhumant pastoralists in the High Atlas Mountains in the face of volatile

rainfall and plant growth. Besides traditional strategies, which are largely based on mobility decisions and herd management, modern income-generating strategies are increasingly important for local livelihoods. We present data on the socioeconomic framework and relate them to management decisions in years with different availabilities of fodder resources on local pastures.

Principal resource management strategies

Five interdependent strategies of pastoral range management can be distinguished: mobility, diversity, flexibility, reciprocity, and reserve (Fernandez-Gimenez and Le Febre 2006). Mobility is used to access natural resources in different localities or regions on the intraseasonal and interseasonal levels (Adriansen 2005; Dwyer and Istomin 2008). Different sets of practices and rules for larger-scale movements, between different pasture types (macro-mobility), and smaller-scale movements, around waterholes and temporal settlements (micro-mobility), can be distinguished (Niamir-Fuller 1998). Diversity refers to the variety of vegetation types exploited by pastoralists. Flexibility refers to socioeconomic strategies to cope with environmental variability. These strategies include various measures of animal husbandry, such as herd diversification and the sale or slaughter of livestock, as well as the use of alternative monetary income. Reciprocity is expressed as social networks constituting an informal insurance that buffers resource variability (McAllister et al. 2006b). Reserve mechanisms serve as an ecological or economic buffer for times of resource scarcity (Frank et al. 2006). For example, pastures are set aside as grazing reserves for drought times (Retzer et al. 2006; Müller et al. 2007), and monetary income from other sources is used to support the herds.

Material and Methods

Data were collected on the southern slopes of the High Atlas Mountains among the Ait Toumert, a pastoral-nomadic Berber fraction that consists of 29 households with an average size of ten members. While sheep and goats are relevant for livestock production, donkeys, mules and camels are used for transportation. The Ait Toumert practice an annual transhumance. The normal transhumance cycle runs along a steep altitudinal gradient, from the mountainous summer pastures at 3,000 m (above sea level) to the lowland ranges at 1,300 m, used during the winter months, passing the intermediate pastures in-between. As in other transhumant societies (Niamir-Fuller 1998), the schedule and distances of transhumance may deviate from this normal transhumance cycle (see also sect. II-5.3), depending on rainfall, herd dynamics, and socio-cultural factors.

To analyze pastoralists' resource management strategies and implications for livelihood security, we use an approach developed for a neighboring Berber fraction to classify household livelihoods (Breuer 2007). Type A households are households ex-

clusively practicing pastoral-nomadism, Type B households are households that combine pastoral-nomadism and wage labor, and Type C households have alternative income sources through formal employment or international migration of household members. Hence, Type A has less access to alternative income sources than the other two types. Accordingly, household wealth increases from Type A to Type C. We collected data on the specific socioeconomic situation of three Ait Toumert households representing these three types with the aid of semi-structured interviews. We analyzed pastoral-nomadic management strategies in years with different availabilities of natural fodder resources. Informants were asked to specify individual mobility decisions in years with good, average, bad, and very bad fodder resource availability, and also were asked which alternative management strategies they had used.

Results

Table II-5.1.3 summarizes the important socioeconomic parameters related to the livelihood security of the three Ait Toumert households. The richer a household, the larger it is, and the higher the number of livestock animals per household member. While in the rich type C households, we counted fifty animals for every household member, only half this number was found in poor households. According to this unequal distribution, only the rich households are satisfied with their herd size, while both poorer households (types A and B) perceive their herd size as insufficient for livelihood security and would prefer to have larger herds. Alternative income from wage labor contributes about a fifth of the total income of the two households of Type B and Type C.

Table II-5.1.3: Differences in socio-economic parameters in the three Ait Toumert households representing the three pastoral livelihood types.

Socio-economic parameter	Variables	Type A: poor	Type B: average	Type C: rich
Family structure	De Jure members	7	9	24
Alternative income sources	Income from wage labour	none	22%	21%
	Financial support per year and person	none	2,750 DH/a	1,600 DH/a
	Gardening (Agriculture)	no	no	yes
Livestock resources	Herd size / de jure member	21	39	50
	Satisfaction with herd size	satisfied	+143%	+267%

Note: For further explanations, see text

Traditional and modern management strategies

The socioeconomic framework clearly influences decision-making processes for range management strategies in different types of years (see table II-5.1.4). Which strategy is chosen from the set of traditional and modern strategies (the latter are feed supplementation, reduced mobility, truck transport, and mass selling of animals) depends on a household's wealth.

Whereas the traditional full transhumant cycle, i.e., a macro-mobility between different pasture types, is practiced by all household types in average and good years, mobility is constrained to micro-mobility during good and very bad years; households tend to stay on one pasture type. Decisions for reduced mobility are often combined with other modern strategies of herd management. In years of very short natural fodder supply, herdsmen keep their animals in barns and rely on feed supplementation. This is particularly practiced by poor households of av-

Table II-5.1.4: Management strategies of three Ait Toumert households related to their socio-economic framework and the availability of natural fodder resources in a particular year.

Type of year	Herd management strategies	Management strategies selected by a household type		
		Type A: poor	Type B: average	Type C: rich
	Full transhumance cacle	-	Yes	Yes
	Reduced mobility	-	-	-
Good year	Feed supplementation	Yes	Yes	Yes
	Truck transport	-	-	-
	Mass selling of animals	-	-	-
	Full transhumance cycle	-	-	-
	Reduced mobility	Yes	Yes	-
Average year	Feed supplementation	Yes	Yes	Yes
	Truck transport	-	-	-
	Mass selling of animals	-	-	-
	Full transhumance cycle	-	Yes	-
	Reduced mobility	Yes	Yes	-
Bad year	Feed supplementation	Yes	Yes	Yes
	Truck transport	-	-	Yes
	Mass selling of animals	-	-	-
	Full transhumance cycle	-	-	-
Very bad year	Reduced mobility	Yes	-	-
(drought year)	Feed supplementation	Yes	Yes	Yes
	Truck transport	-	Yes	Yes
	Mass selling of animals	-	Yes	-

Note: Years were classified by local herdsmen into having 'good", 'average", 'bad", and 'very bad" availability of fodder resources on local pastures. The four modern strategies which have evolved during the past decades are shown in bold.

erage or low income. However, feed supplementation has become a common practice, irrespective of the type of year (which reflects the availability of fodder resources on pastures) and the type of household (reflecting a household's wealth, see table II-5.1.4). Some informants stated that they did not move to remote winter pastures in spite of good forage availability because they had already bought food for the unpredictable winter time. Food supplementation was originally introduced by the government during a drought in the 1980s. As households today can buy additional food on a market close to the intermediate or near winter pastures, they tend to stay at that place, irrespective of the year's rainfall and thus forage supply.

Coping with drought

Truck transport is another new strategy used to cope with fodder resource scarcity. While the majority of households remain on the near winter pastures of the Ait Toumert territory, households of type B and C, which have access to alternative income sources, can afford to rent a truck to transport their herds to far-off pastures. The wealthy Type C households, with the best access to alternative livelihood resources, relies on truck transport in bad years, while the intermediate Type B only resorts to this strategy in years of severe drought. The mass selling of animals is only practiced by the household with moderate wealth (Type B) in a drought situation.

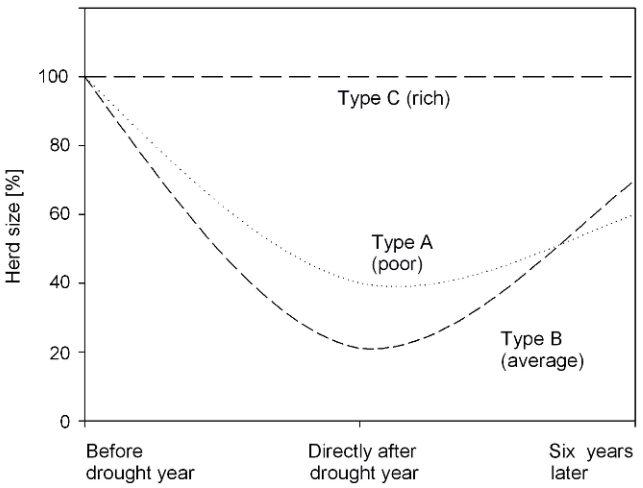

Fig. II-5.1.9: Herd size dynamics of the three Ait Toumert households during and after a drought event. Herdsmen were interviewed in October 2007. The herd size prior to a drought event (in the years 2000/01) is set as 100%. 'Directly after drought year' is the herd size remembered by the herdsmen for the end of 2001, and 'six years later' is the herd size at the end of 2007. For the classification of household types, see text.

The different management strategies aim to minimize famine-induced mortality of livestock, i.e., animal losses related to scarce fodder resources. All households are successful in this task in good, average, and bad years; no animal losses were reported by informants. The rich household (Type C) maintained a stable herd size with constant birth and sale rates even in a drought situation. In contrast, substantial losses of animals were reported by the households of average wealth (79% of animals) and poor wealth (40% of animals; see fig. II-5.1.9). After the drought, Type B households were able to restock livestock faster than Type A households.

Modern range management strategies: Implications for livelihood security, and resilience

The traditional herd management of the Ait Toumert makes use of and creates reliable fodder resources, which are ecological buffers against environmental variability (see also sect. II-5.3). Ecological buffers can minimize animal losses during times of fodder resource scarcity, thus securing household livelihoods. However, Ait Toumert herdsmen are not as dependent on ecological buffers as they used to be. Socioeconomic resources and individual networks functioning as economic buffers become increasingly important (see table II-5.1.3). The strategies of herd management named by Ait Toumert herdsmen can be classified into mobility, diversity, flexibility, and reserves (see table II-5.1.5), which are four of the five principal strategies identified in pastoral-nomadic management (Fernandez-Gimenez and Le Febre 2006). Besides these strategies named by local herdsmen, reciprocal grazing agreements with neighboring factions, alternative monetary income from wage labor, and socioeconomic reciprocity have also been observed as specific strategies of the Ait Toumert (see table II-5.1.5).

Table II-5.1.5: Principal management strategies used by pastoral nomads, and specific strategies of Ait Toumert herdsmen. Modern strategies that have evolved during the past decades are shown in bold.

Principal strategy	Specific strategies of the Ait Toumert
Mobility	Macro-mobility (transhumance); reduced mobility; truck transport
Diversity	Diversification of livestock (goats, sheep); transhumance; truck transport
Flexibility	Mass selling of animals; alternative monetary income
Reserve	Temporal resting of pastures via the agdal institution (see chapter II-6.3); feed supplementation
Reciprocity	Reciprocal grazing agreements for winter pastures; reciprocal acceptance of 'grazing tourism' via truck transport

Note: Modern strategies which have evolved during the past decades are shown in bold.

As is typical of recent changes in pastoral societies (Bollig 2006; Moritz 2008), modern strategies adopted in the last decades have led to a diversification of the Ait Toumert's set of strategies. The numbers of both specific and principal strategies have increased. Furthermore, we observed strong social stratification. While a wealthy household shows high diversification and makes full use of modern strategies, the livelihood security of poorer households is more dependent on traditional resource management. These observations are consistent with other studies from rural Africa, which report a strongly wealth-differentiated pattern of income diversification (Barrett et al. 2001). An increasingly skewed distribution of wealth in rural Africa may result from this development (Reardon et al. 2000).

Like the traditional mobility strategies, the modern strategies seek or create reliability within the social-ecological system by buffering resource variation (Roe et al. 1998). A larger portfolio of resource management and income-generating strategies increases the individual resilience of households to face external shocks such as droughts (Desta and Coppock 2004). This is the reason that there have been many recommendations and attempts, particularly in sub-Saharan Africa, to make nomadic pastoralists diversify their mode of subsistence. National governments and international development agencies claim that it is important for nomads not to depend on only one source of income. Ensuing diversification projects have often been carried out in conjunction with attempts at sedentarizing nomads (Pedersen and Benjaminsen 2008).

However, a diversification of management strategies may increase the system's vulnerability to collapse. This is because households increasingly rely on economic buffers instead of ecological buffers provided by the natural resource system (Frank et al. 2006). A diversification of income sources in a pastoral society is thus accompanied by weaker links between the society and its environment. This weakening may lead to an overall decrease in a pastoral system's resilience due to a weakening of environmental feedback (McAllister et al. 2006a). Modeling approaches are needed to assess wealth dynamics on the levels of households and societies under conditions of increased climatic variability (Lybbert et al. 2004), and to analyze how a social-ecological system's vulnerability is affected by a wealth-differentiated diversification of income strategies.

II-5.1.5 Modeling vegetation dynamics as related to pastoralists' grazing activities in the Drâa basin rangelands

Background and Methods

In addition to irrigated cropping in the oases of the Drâa valley, extensive livestock grazing by pastoralists is the major land use in the rangelands that make up the majority of the region. Human-controlled grazing intensities affect the spatio-

temporal vegetation composition and the hydrological cycle in semi-arid to arid rangelands. Increasing herd populations as a strategy to offset climate variability leads to enhanced degradation of vegetation and soils and exploits the water resources extensively. It is, therefore, imperative to manage grazing intensities and maintain the productivity of dryland ecosystems.

Dry rangelands are characterized by low annual biomass productivity, which is only partly consumable even by specialists like goats, sheep and dromedaries. To analyze the impacts of varying stocking rates together with Climate Change scenarios, we primarily initialized the spatially explicit ecosystem model SAVANNA (Coughenour 1993). During this approach, the model computes herbivore herds constituted by sheep, goat and dromedary grazing activities for herbaceous, shrub and tree biomass in a high spatial resolution. In order to simulate plant growth, the plant functional groups (PFT) approach is used. This enables the model to assume plant groups instead of individuals and calculate PFT responses (e.g., to grazing). However input data, including shrub and grass leaf biomass and physiology, soil and vegetation maps, must be provided to simulate the vegetation of different landscapes. The model computes outcomes (e.g., PFT's aboveground net primary production (ANPP)) with PFT inherent parameters (e.g., photosynthesis). The results are provided by either plots of temporal development (e.g., for grass PFT leaf development (see fig. II-5.1.10)) or spatial maps with model specific spatial resolution (1 km^2) (e.g., for herbaceous PFT ANPP). In addition, information on hydrological parameters and plant group species interactions on simulation time scales is produced.

Results

Figure II 5.1.10 summarizes annual livestock densities derived from census data in the province of Ouarzazate, suggesting a strong link between herd numbers (sheep and goats) and precipitation. The high numbers of animals seen in the early 1980s are an artifact of higher rainfall amounts in the late 1970s, and later reduced rapidly due to an absence of rainfall. Although rainfall decreased over the last decade of the 20th century, sheep and goat numbers were maintained at a comparatively high level of approximately 800,000 heads. These real animal numbers and precipitation amounts are implemented in the model to simulate a baseline scenario.

The SAVANNA baseline model run (see fig. II 5.1.11) shows how biomass levels are reduced due to decreasing precipitation and a high number of animals. Total biomass increase during the course of one year is parameterized towards the maximum biomass amount at the flowering period in autumn. A new simulation then begins with the new annual biomass development, based mainly on precipitation data. The first five years of the standing biomass simulation must be determined as a model 'warm-up' phase after which a constant biomass level can be predicted. During this model phase, biomass development and precipitation amounts did not support high animal numbers, which is why these numbers de-

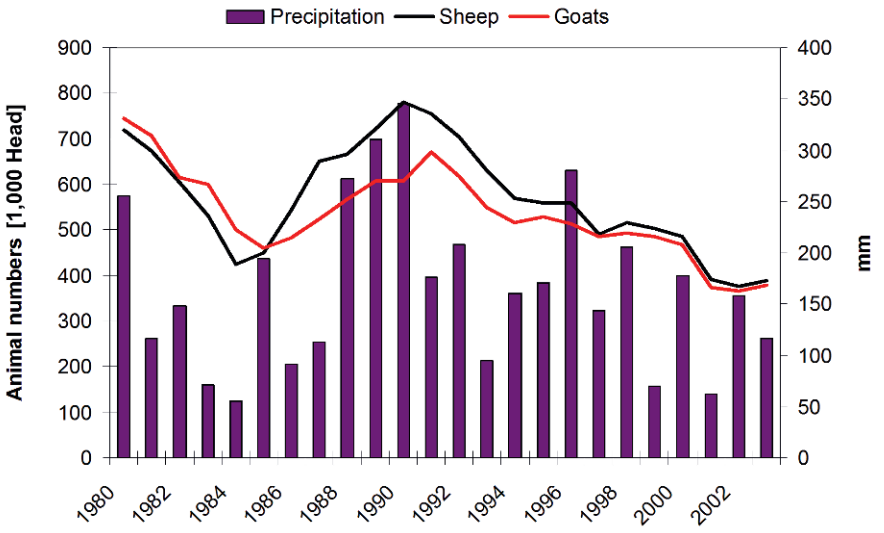

Fig. II-5.1.10: Development of annual livestock numbers (hundred thousands) by census data for the Province of Ouarzazate 1980-2003 and precipitation data of the climate station Ouarzazate (Source: ORMVAO 2005).

crease. Total biomass amounts increased as rainfall increased, which led to a slight increase in the number of animals (see fig. II 5.1.10). At the end of the 1990s, biomass amounts maintained a certain level at approximately 200-300 kg ha^{-1}. This level serves as a baseline run to test the model's reliability of simulated biomass with historic livestock numbers.

In order to achieve reliable scenarios of future Climate Change, we used the IPCC climate scenarios A1B and B1 downscaled to the basin of Ouarzazate (IPCC 2007). Using these climate data, different scenarios regarding herd sizes are calculated (see fig. II 5.1.12). Here, the downscaled IPCC scenario A1B is used to simulate the heavy stocking rates of 900,000 heads of sheep, goats, and dromedaries for the Basin of Ouarzazate during the period 2002-2050.

On the basis of input data on the abundance and growth of vegetation, as described in the background paragraph above, the model predicts biomass production [kg ha^{-1}] in terms of specific PFT. These PFT are calculated for herbaceous plants (grass) as well as for the shrub and tree layers. Each of these layers consists of various plant groups; the major groups for herbaceous PFT here are fine, coarse and alpine grasses. Based on the climate conditions and grazing preferences of animals, the temporal evolution of these plant types are simulated (see fig. II 5.1.13). The first ten years of simulation must be determined as the model 'warm-up' phase in order to find the climatic adaptation of biomass production. In this example, the types 'fine grass' and 'alpine grass' are highly preferred in animal diets. Whereas the 'fine grass' maintains a constant level of accumulated bio-

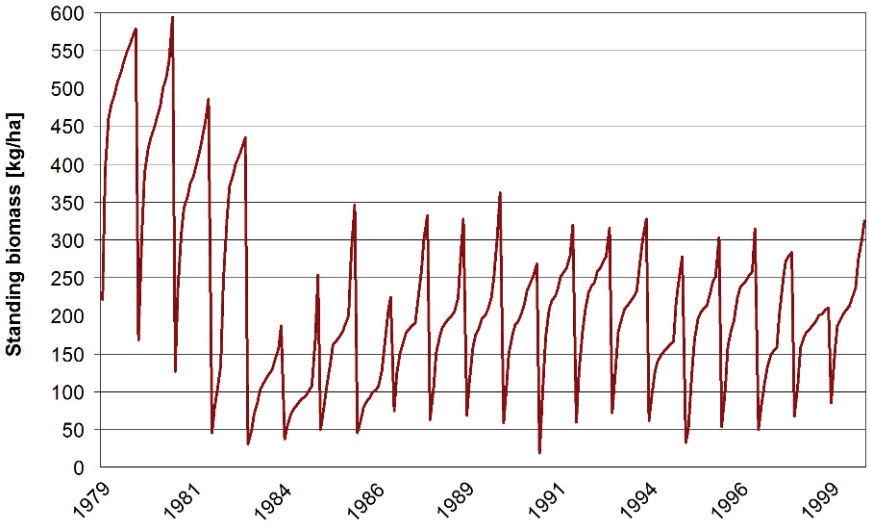

Fig. II-5.1.11: Simulated monthly total standing biomass [kg ha^{-1}] for the basin of Ouarzazate.

mass throughout the simulations, 'alpine grass' is predicted to decrease, probably due to its restricted appearance in niches in the study area. Somewhat surprisingly, 'coarse grass', despite its low digestibility, slightly decreases during the 40 years of simulation due to climatic changes. Model outcomes suggest a higher impact of stocking rates on herbaceous and shrub ANPP development than climatic

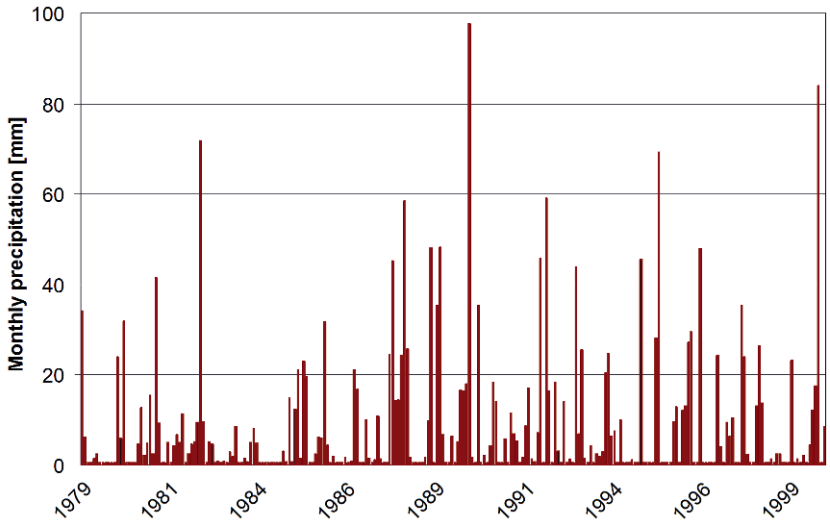

Fig. II-5.1.12 Simulated monthly precipitation [mm] (Ouarzazate climate station), 1979-2000.

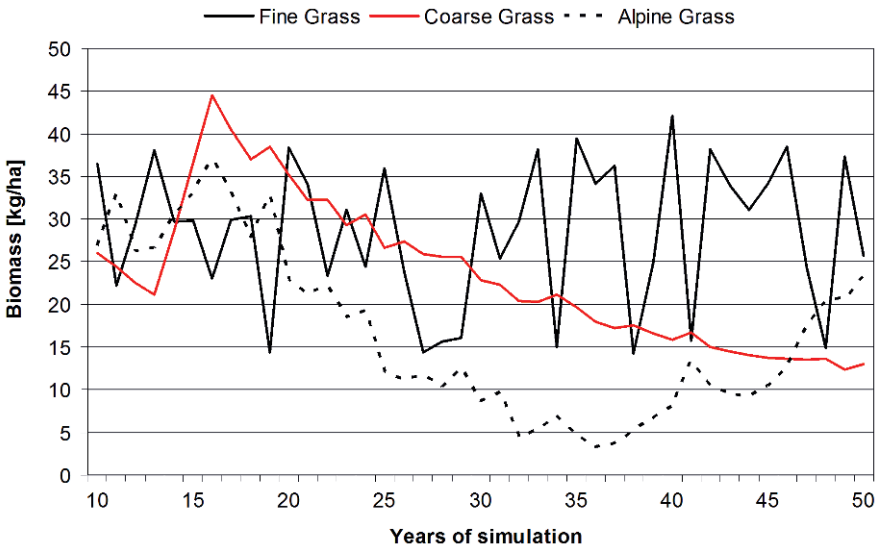

Fig. II-5.1.13: Development of fine, coarse, and alpine grass, accumulated to annual leaf biomass [kg per ha] for a simulation period of 40 years.

changes, as expressed in the IPCC scenarios. Furthermore, heavily grazed PFT groups such as fine grass are able to maintain a constant stock of biomass development. This result suggests that palatable plants regulate grazing stress through certain adaptation strategies. Unpalatable plants, however, are predicted to decrease in ANPP amounts during the simulation period. This fact still requires study and an improvement in further modeling investigations of the impact of livestock on vegetation in the Drâa catchment. The SAVANNA model successfully simulates herbivores' biomass interactions in a semi-arid catchment in which vegetation development is correlated to rainfall patterns. The evolution of nitrogen budgets, plant water consumption and animal conditions are likewise computed by the SAVANNA model. Model calculations of variations in climate scenarios and stocking rates help us to evaluate the resilience of vegetation against grazing impacts. This may help to understand and appropriately simulate ecosystem functioning, and to reliably predict changes over space and time.

Model runs may be used to determine specific highly vulnerable and sensitive areas and protect plant types from grazing. Additionally, model outcomes, specifically vegetation cover and abundance, may be used in economic models as well.

II 5.1.6 Conclusions

Two important links between resource use and livelihood security were described in this section: while cropping in the Drâa oases heavily depends on water availability, transhumant livestock husbandry relies on land and vegetation productivity. The two main agricultural production modes are practiced by different ethnic groups with different organizational forms, using different technologies, and producing different products. An important common characteristic is that both production modes rely directly or indirectly on rainfall, and therefore are heavily exposed to short-term climate variability. Moreover, both production modes must manage problems resulting from the "tragedy of the commons" (Hardin 1968). In the case of farmers, water for irrigation is the contested resource, while herdsmen have to manage pastures in a sustainable way.

The livelihoods of the inhabitants of the Drâa basin were more heavily dependent on agricultural production in earlier times than they are today. As discussed in section II-5.4, labor migration and tourism increasingly help to diversify the sources of income for farm and pastoral households. The impact of these additional sources of income on the intensity of resource use remains an open question. Several different incentive patterns might conceivably be at work here, depending on the resource endowment of the individual farm household and the source of additional income.

First, non-farm income might substitute farm income. This may be the case in families where labor resources to continue farming have become scarce after the outmigration of young members that leaves only child-raising women and the elderly in the village. If this were the case, farming would be largely abandoned, and the land or water rights of the family would be leased out, not leading to an additional use of resources. However, if the labor resources of the household are still idle, the household might use additional monetary resources to invest in non-farm economic activities, education, or housing. In terms of resource use, this alternative would also be largely neutral. If, however, farm households decide to invest in technology that enables a more effective extraction of resources, such as motor transport during transhumance or motor pumps for groundwater extraction, resource use and the resulting pressure on local and regional resource endowments might increase. This latter result becomes more likely the greater the preferences of resource users for continuing the resource-using activities. To properly farm their own fields or to own a large livestock herd usually raises the reputation of family heads among their peers and strengthens the influence of the family in local decision-making bodies. The increasing number and use of motor pumps in the Drâa oases, as well as the rising importance of the motorized transport of livestock during transhumance, both indicate that land and water resources will remain under pressure despite their diminishing importance to total family income.

References

Adriansen HK (2005) Pastoral mobility: a review. Nomadic Peoples 9:207-214

Barrett CB, Reardon T, Webb P (2001) Nonfarm income diversification and household livelihood strategies in rural Africa: concepts, dynamics, and policy implications. Food Policy 26:315-331

Bollig M (2006) Risk management in a hazardous environment - a comparative study of two pastoral societies. Springer, New York

Breuer I (2007) Livelihood security and mobility in the High Atlas Mountains. In: Gertel J, Breuer I (eds) Pastoral Morocco: globalizing scapes of mobility and insecurity, pp. 165-179. Reichert, Wiesbaden

Coughenour M (1993) The SAVANNA landscape model–documentation and user's guide. Natural Resource Ecological Laboratory, Colorado State University, Ft. Collins, CO

Desta S, Coppock CP (2004) Pastoralism under pressure: tracking system change in Southern Ethiopia. Hum Ecol 32:465-486

Dwyer M, Istomin K (2008) Theories of Nomadic Movement: A New Theoretical Approach for Understanding the Movement Decisions of Nenets and Komi Reindeer Herders. Hum Ecol 36:521-533

FAO (1979) Soil survey investigations for irrigation. FAO Soils Bulletin 42. FAO, Rome

Fernandez D, Lourd M, Ouinten M, Tantaoui M, Geiger JP (1995) Le Bayoud du palmier dattier. Phytoma 469:36-39

Fernandez-Gimenez ME, Le Febre S (2006) Mobility in pastoral systems: Dynamic flux or downward trend? Int J Sust Dev World 13:341-362

Frank K, Baumgärtner S, Becker C, Müller B, Quaas M (2006) Ecological-economic models for sustainable grazing in semi-arid regions: between concepts and case studies. In: Leser H (ed) The Changing Culture and Nature of Namibia: Case Studies, pp. 69-89. Basler Afrika Bibliographien, Basel – Windhoek

Gresens F (2006) Untersuchungen zum Wasserhaushalt ausgewählter Pflanzenarten im Drâa-Tal Südost Marokko. Bonner Agrikulturchemische Reihe, Band 26. Institut für Nutzpflanzenwissenschaften und Ressourcenschutz, Bonn

Hardin G (1968) The Tragedy of the Commons. Science 162(3859):1243-1248

Heidecke C, Kuhn A, Klose S (2008) Water pricing options for the Middle Drâa river basin in Morocco. AfJARE 2(2):170-187

IMPETUS (2006) West Africa: An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa. Second Final report 2003-2006. University of Cologne, Institute of Geophysics and Meteorology, Cologne

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kirscht H (2008) Agricultural Strategies: Irrigation Management, Risk Diversion and Crop Rotation in Tichki. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp. 73-74. Department of Geography, University of Bonn, Bonn

Kourdi M (1996) Contribution à la maîtrise de la distribution de l'eau d'irrigation dans le périmètre du Drâa moyen. Master thesis, Faculty of Agricultural Sciences, Rural Engineering Unit, Catholic University of Leuven

Lybbert TJ, Barrett CB, Desta S, Layne Coppock D (2004) Stochastic wealth dynamics and risk management among a poor population. Econ J 114:750-777

MADRPM (2000) Recensement Général de l'Agriculture: Résultats par Commune, 1996/97. Ministère de l'Agriculture, du Développement Rural et des Pêches Maritimes, Rabat

McAllister RRJ, Abel N, Stokes CJ, Gordon IJ (2006a) Australian pastoralists in time and space: the evolution of a complex adaptive system. Ecol Soc 11:41

McAllister RRJ, Gordon IJ, Janssen MA, Abel N (2006b) Pastoralists' Responses To Variation Of Rangeland Resources In Time And Space. Ecol Appl 16:572-583

Moritz M (2008) Competing paradigms in pastoral development? A Perspective from the Far North of Cameroon. World Dev 36:2243-2254

Müller B, Linstädter A, Frank K, Bollig M, Wissel C (2007) Learning from local knowledge: Modeling the pastoral-nomadic range management of the Himba, Namibia. Ecol Appl 17:1857-1875

Niamir-Fuller M (1998) The resilience of pastoral herding in Sahelian Africa. In: Berkes F, Folke JC (eds) Linking social and ecological systems: management practices and social mechanisms for building resilience, pp. 250-284. Cambridge University Press, Cambridge

ORMVAO (2005) Office régionale de Mise en Valeur- PAGER - Études des resource en eau. Ouarzazate

Pedersen J, Benjaminsen T (2008) One Leg or Two? Food Security and Pastoralism in the Northern Sahel. Hum Ecol 36:43-57

Penitsch R, Rademacher C, Rössler M (2005) Population Dynamics in the Drâa Catchment. Poster presented at the GLOWA conference, Cologne 18.-19. May

Reardon T, Taylor JE, Stamoulis K, Lanjouw P, Balisacan A (2000) Effects of non-farm employment on rural income inequality in developing countries: an investment perspective. J Agr Econ 51:266-288

Retzer V, Nadrowski K, Miehe G (2006) Variation of precipitation and its effect on phytomass production and consumption by livestock and large wild herbivores along an altitudinal gradient during a drought, South Gobi, Mongolia. J Arid Environ 66:135-150

Roe E, Huntsinger L, Labnow K (1998) High reliability pastoralism. J Arid Environ (39):39-55

Schulz O, Busche H, Benbouziane A (2008) Decadal precipitation variances and reservoir inflows in the semi-arid Upper Drâa basin (south-eastern Morocco). In: Zereini F, Hötzl H (eds) Climatic Changes and Water Resources in the Middle East and in North Africa, pp. 165-178. Springer, Heidelberg

Tsur Y, Roe T, Doukkali R, Dinar A (2004) Pricing Irrigation Water – Principles and Cases from Developing Countries. RFF Press, Washinton DC

II-5.2 Impacts of Global Change on water resources and soil salinity in Southern Morocco

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Abstract

Global change will increase the pressure on water resources, especially in regions with high water scarcity like the southern part of Morocco. Scenario calculations with adapted, calibrated and validated models reveal a decline in surface water availability for the Upper Drâa valley up to 2020 due to a decrease in rainfall. Snow coverage will also decrease in the future, caused by an increase in air temperature. Moreover, the climate scenarios show a trend towards shorter return periods of drier years in future. The climate signal is stronger than the uncertainty caused by the different downscaling techniques, which had to be developed because the resolution of the climate data does not fit to the resolution of the hydrological model.

Reduced surface water availability will increase the pressure on the groundwater resources downstream of the Mansour Eddahbi reservoir because irrigation demand is high. Climate scenarios as well as socio-economic scenarios reveal significant impacts on water resources. Due to limited fresh water from the reservoir, soil and groundwater salinity will increase in the future, eventually causing failure in food production if no appropriate measures are undertaken. While surface water availability will not be a limiting factor for the upstream oases, an adapted resource management for the oases downstream of the reservoir is indispensable.

Keywords: Southern Morocco, Drâa valley, climate scenario, socio-economic scenario, PRO-RES Monitoring Tool, Hydraa SDSS, IWEGS SDSS, snow storage, reservoir inflow, surface water availability, groundwater availability, soil salinity

II-5.2.1 Introduction

Given that decadal predictions of water availability are not actually realizable, analyses of scenarios describing possible future development are a standard approach to sensitize and prepare for changes. Realistic scenario projections require a thorough understanding of current processes and water balances as well as reli-

able story lines concerning Global Change (see chap. II-3). This process knowledge is condensed in a number of simulation models, which are described in detail in section I-6.2. Models, data and scenario assumptions are combined in Spatial Decision Support Systems (SDSS) (see chap. II-2), which can be used to analyze the effects of probable Global Change on water-related aspects in Southern Morocco. Following the main pathway of the water flow within the study area, this section is organized in three subsections. These deal with snow in the High Atlas Mountains (PRO-RES Monitoring Tool), the hydrological processes in the Upper Drâa basin (Hydraa SDSS) and groundwater-related aspects of the Middle Drâa valley (IWEGS SDSS).

II-5.2.2 Seasonal snowmelt runoff forecast for the management of the Mansour Eddahbi Reservoir

All tributaries of the Central High Atlas Mountains join at the Mansour Eddahbi reservoir. For water availability in the Middle Drâa valley (quantity of irrigation water, number of water releases from the reservoir, quality of drinking water), the short-term and the long-term development of precipitation is important. Considering the fact that a large percentage of winter precipitation falls as snow in the high mountain region (see fig. I-6.2.2), there are two leading questions:

1. How does Climate Change influence snow storage in the high mountains and the discharge of the Mansour Eddahbi reservoir tributaries near the town of Ouarzazate on a long-term perspective?
2. How much water will the high mountain rivers deliver to the reservoir within the next months?

The future quantity of snow and of total precipitation in the High Atlas Mountains and in the Basin of Ouarzazate is estimated based on climate scenarios. These scenarios are the results of the statistical downscaling method described in subsection II-3.2.6. Question two can be answered if knowledge about the current snow mass (or snow water equivalent) at an appointed date as well as a seasonal weather forecast is available. In the monitoring tool PRO-RES (Prognosis of snowmelt runoff for the Reservoir Mansour Eddahbi), current measurements and statistical forecasts of the weather generator are coupled with the Snowmelt Runoff Model SRM (Martinec 1975). The calculated river discharge is then transferred to the reservoir with respect to water losses from the river (see subsect. I-6.2.2). The acquisition of temperature, precipitation and runoff measurements from stations in the Upper Drâa valley is an important prerequisite.

The regional discretization of PRO-RES follows the distribution of hydrological stations run by the regional water authority (*Service Eau de Ouarzazate*). At these stations, atmospheric parameters, water levels and stream velocity are measured. As can be seen in figure II-5.2.1, nine sub basins were defined. These cover 15,000 km² with a difference in altitude of about 3,000 m ranging from 4,071 m asl

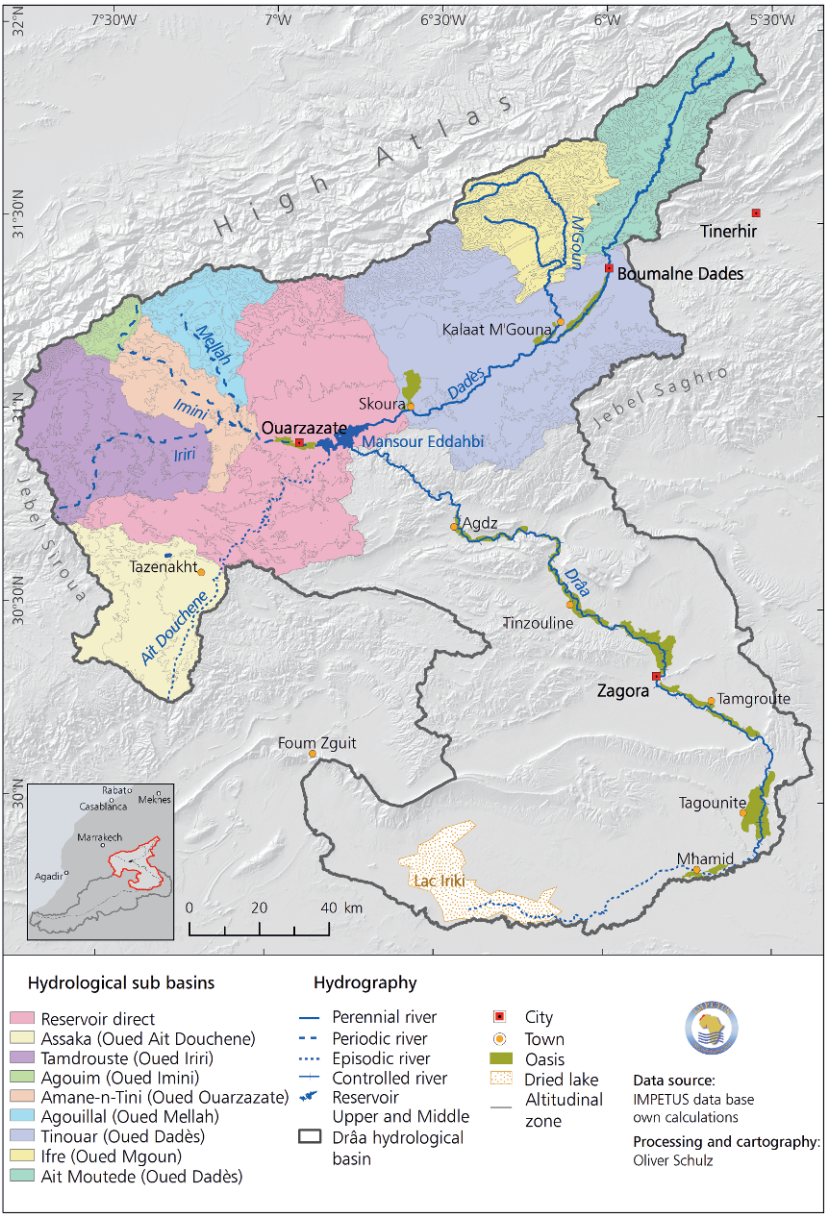

Fig. II-5.2.1: Regional discretization of the Upper Drâa basin for the PRO-RES monitoring tool with nine sub basins and altitudinal zones of 250 m.

(peak of Jebel M'Goun) to 1,050 m asl (Mansour Eddahbi reservoir). In each sub basin, an altitudinal zoning of 250 m was chosen to consider the gradients in temperature and precipitation. Another input variable to the SRM was the daily snow cover within the altitudinal zones. To derive these values from satellite data, daily MODIS images were used (product MOD09 delivered by the United States Geological Survey, USGS) and analyzed in the module *MODISsnowmap*. The free available Modis Reprojection Tool MRT (by USGS) was integrated in the SDSS-Framework for re-projection of the satellite images (see subsect. II-2.4.3). The resulting snow masks were intersected with the zoning of the Upper Drâa valley resulting in the percentage of snow cover. Currently, the satellite database consists of about 400 images representing the snow cover periods from 2001 to 2008.

At the beginning of the modeling process, the database and the simulation period had to be chosen. The choice of sub basins is crucial for the following modeling process because a result for the total inflow and filling level of the reservoir is only achievable if all sub basins are selected. For climate data input, the user has a choice between measured data and climate scenario data. In the seasonal forecast option, measured data is chosen up to a specified day by the user. Consequently, climate scenario data is chosen for the rest of the season.

The choice of simulation period depends on the database, which is currently limited to the period 2001 to 2006 for measured data and 2001 to 2020 for the scenarios. Seasonal forecasts using a mix of measured data and scenarios can be calculated only up to the end of the currently chosen hydrological year. For more technical details see subsection II-2.4.3.

Results of scenario modeling with PRO-RES

Using the available climate scenarios, reservoir inflow scenarios have been calculated for the period 2001 to 2020. It must be recognized that the SRM is a conceptual snowmelt runoff model and that the PRO-RES tool uses a simplified approach for the discharge transfer into the reservoir. A more detailed analysis of the hydrological processes is presented in subsection II-5.2.3. The data for PRO-RES are provided by the SMGHydraa weather generator as a result of the statistical downscaling of the climate scenarios (see sect. II-3.2). Climate scenarios based on IPCC SRES scenarios A1B and B1 until 2020 are calculated in the IMPETUS project. Results are then regionally downscaled for the Drâa basin, including the High Atlas Mountains and the Drâa valley. As climate scenario data are modeled with a statistical and dynamical approach, they provide a statistical representation of the possible future climate (see sect. II-3.2). These statistical results cannot be applied as real predictions to defined time periods. Therefore, the modeled reservoir inflow is only a representation of inflow characteristics but is not related to one of the specific years from 2001 to 2020. For the application of PRO-RES as a monitoring tool, efforts must be continued to improve seasonal weather forecasts as a base for seasonal runoff modeling.

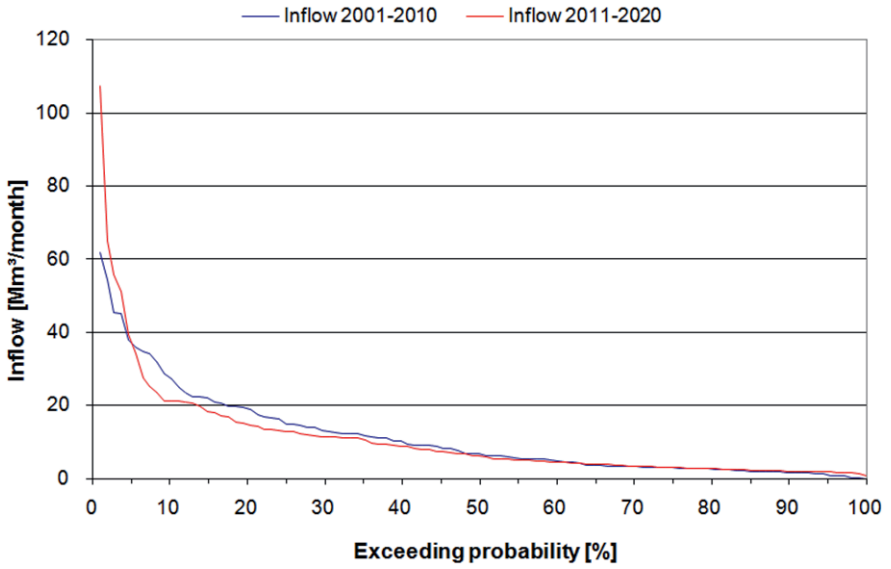

Fig. II-5.2.2: Exceeding probability of the monthly mean reservoir inflow for 2001 to 2010 and 2011 to 2020 modeled with PRO-RES based on climate scenario A1B (regionalization of climate data: SMGHydraa).

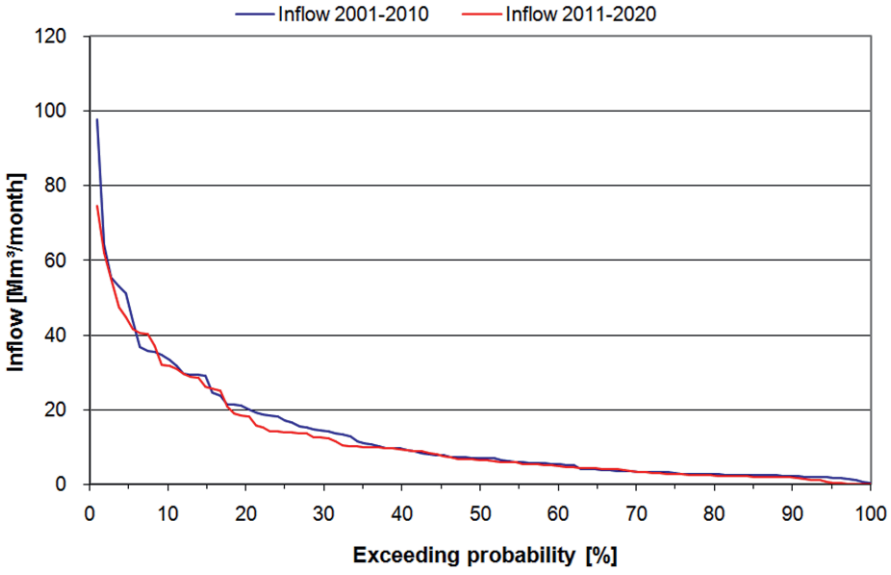

Fig. II-5.2.3: Exceeding probability of monthly mean reservoir inflow for 2001 to 2010 and 2011 to 2020 modeled with PRO-RES based on climate scenario B1 (regionalization of climate data: SMGHydraa).

The modeled reservoir inflow for 2001 to 2020 shows an expected inter-annual variability as is typical for arid regions. Accordingly, the standard deviation of monthly reservoir inflow is higher than the monthly average. For climate scenario A1B, there is a trend toward higher variability in the second decade, whereas the number of medium wet periods decreases (see fig. II-5.2.2). As an example, the exceeding probability of 20 Mm^3/month of inflow, which is 20% in the first decade, reduces to 14% in the second decade. However, in five months within the second decade, inflow will be higher than in the first decade. In climate scenario B1, the monthly mean reservoir inflow (2001-2020) is 12 Mm^3, which is 10% higher than for climate scenario A1B (11 Mm^3). In B1, the standard deviation of the mean higher inflow value for climate scenario B1 can be interpreted as a minor change in climate compared to the climate A1B scenario. This is underlined by nearly identical exceeding probabilities in both decades, as is shown in figure II-5.2.3.

II-5.2.3 Global change effects on hydrological processes in the Upper Drâa catchment

In this study, Climate Change scenarios have been used to estimate impacts of future Climate Change on water availability in the Upper Drâa region. The IPCC SRES climate scenarios A1B and B1 with three ensemble members have each been derived from the Regional Model REMO (Paeth et al. 2009). Since neither of the scenarios evoke significantly different trends for Morocco (Born et al. 2008), all six ensembles were used for a combined scenario analysis within this study. This study compares the periods 1970 to 2000 and 2001 to 2030. While the temperature increases by about 0.3 to 0.8 °C, changes in precipitation vary to a larger extent, exhibiting distinctions between the basin and the mountainous region (see sect. II-3.2).

As previously noted, a weather generator has been developed which fits data to orographic details (elevation, exposition, etc.) that are not considered within REMO (see sect. II-3.2). However, model biases (25% more precipitation simulated by REMO compared to measurements) remain in the data and therefore prohibit direct use within a hydrological model. Consequently, four different downscaling techniques have been used to generate usable time series (see table II-5.2.1). As proposed by Arnell et al. (2003), Climate Change effects are derived from the comparison of control runs (1971-2000) and scenarios (2001-2030). The measured data ranging from 1978 to 2007 is considered equivalent to the period 1971 to 2000 and is therefore referred to as the "baseline model run." Future changes as simulated by the climate model are added to the measured data and referred to as climate scenario.

Table II-5.2.1: Downscaling techniques for scenario analysis.

Downscaling	Baseline	Change in monthly rainfall	Change in monthly temperature	Character
A	Measured	Decrease: Number of wet days Increase: Relative per event	Absolute	Higher intensity
B	Measured	Relative per event	Absolute	Lower intensity
C	Measured	Absolute per event	Absolute	Normal
D	Simulated	direct use of model data		As in scenarios

The following downscaling strategies are pursued:

- A relative decrease in precipitation has been converted to a decrease in the number of wet days, whereas a relative increase has been added to events in the respective month, resulting in a scenario with rainfall intensities comparable to or higher than in the baseline scenario (A).
- The second approach has converted relative changes into relative changes of each event, resulting in increased or decreased intensities of the events (B).
- Within the third approach absolute changes of monthly precipitation have been added to single events, leading to (slightly increased or decreased) intensities comparable to the baseline scenario (C).
- A fourth approach directly used the Climate Change. Therefore, only relative changes in the model output could be analyzed (D).

Knowing the deficiencies of each approach, the spread of results using different downscaling techniques is assumed to at least confine the range of reasonable results. Though single components of the water balance can be assessed easily using SWAT (Soil & Water Assessment Tool, Arnold et al. 1993; see sect. I-6.2), inter-annual variability that may change in future periods is not included. Since this approach does not account for changes in inter-annual variability but maintains variability as in the baseline model run, no analysis of future time series was carried out. Instead, annual exceedance probabilities and Climate Change induced effects on the annual water balance will be presented.

Scenario results

Figure II-5.2.4 displays the development of annual discharge exceedance probabilities in the Upper Drâa catchment for the periods 2001 to 2030 compared to 1971 to 2000. The uncertainty range includes the second and third quartile of the

24 scenarios (6 ensembles x 4 downscaling approaches). It is likely that discharge generally decreases (according to the nomenclature proposed by the IPCC, this means a likelihood of occurrence greater than 66% (IPCC 2007)). There are no particular trends for extreme years (dry or wet). One can regard a 300 Mm³/year discharge into the reservoir an acceptable threshold since 250 Mm³/year is required for irrigation of the Middle Drâa oasis (Ministère des travaux publics 1998). Also, roughly 50 Mm³ can be considered as evaporation losses and drinking water supply from the reservoir (though this number highly depends on the filling level of the reservoir). In the baseline model run, this threshold is exceeded in 48% of the years, whereas in the scenario, the threshold is exceeded in only 31% of the years. The changes in annual water balance are given in table II-5.2.2 and figure II-5.2.5. All of the changes addressed are the results of at least 18 out of 24 simulations:

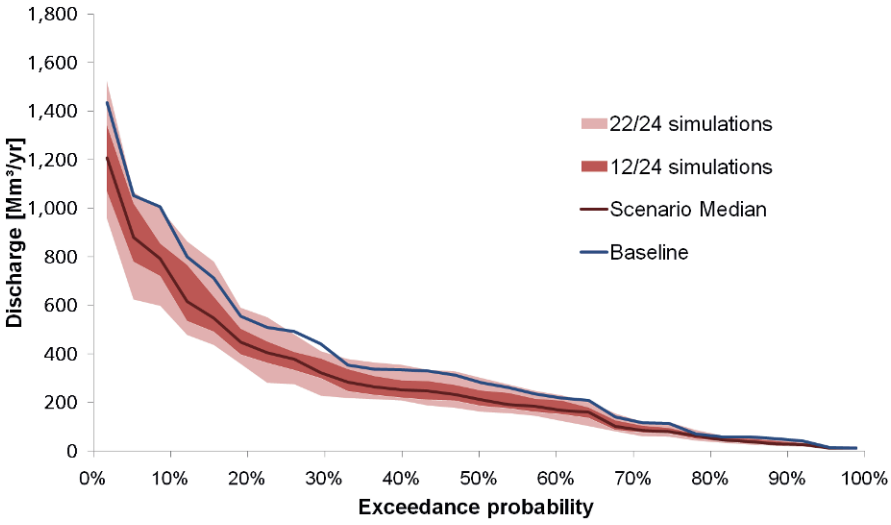

Fig. II-5.2.4: Development of annual discharge exceedance probabilities in the Upper Drâa catchment under Climate Change (1971-2000 and 2001-2030).

Precipitation is likely to decrease by at least 6% with a median of 10%. The projected temperature increase strongly affects snowfall. Therefore, its decrease is the strongest signal in the scenario results. Snowfall is likely to decrease by 13% (median = 17%). Runoff will decrease by 10% (median = 16%). The relative importance of hydrological processes does not undergo a substantial change, though a slight shift in the runoff composition can be observed. Surface runoff decreases in favor of base flow, which can be attributed to the lower intensity of the scenario rainfalls compared to the baseline period.

Considering these uncertainties, the effects of different ensemble runs and different downscaling approaches have been compared (see eq. II-5.2.1): 68% of

Table II-5.2.2: Water balance of the Upper Drâa catchment (14,981 km²), modeled with SWAT2005 (baseline model run and scenario 2001-2030).

	Baseline	Fraction of Precipitation	Scenario (Median)	Fraction of Precipitation
Precipitation	212.5	-	191.0	-
Snow	26.0	12.2%	21.6	11.3%
Rain	186.5	87.8%	169.4	88.7%
- Evaporation	168.6	79.3%	153.0	80.1%
- Direct GW recharge	3.5	1.6%	2.9	1.5%
= Runoff	40.4	19.0%	34.1	17.9%
Surface	19.8	9.3%	16.0	8.4%
Interflow	1.1	0.5%	1.1	0.6%
Baseflow	19.5	9.2%	17.0	8.9%
- Indirect GW recharge	4.5	2.1%	4.0	2.1%
= Channel Discharge	35.9	16.9%	30.0	15.7%
- Irrigation	11.1	5.2%	10.1	5.3%
= Reservoir interflow	24.9	11.7%	19.9	10.4%
Total GW	8.0	3.8%	6.9	3.6%

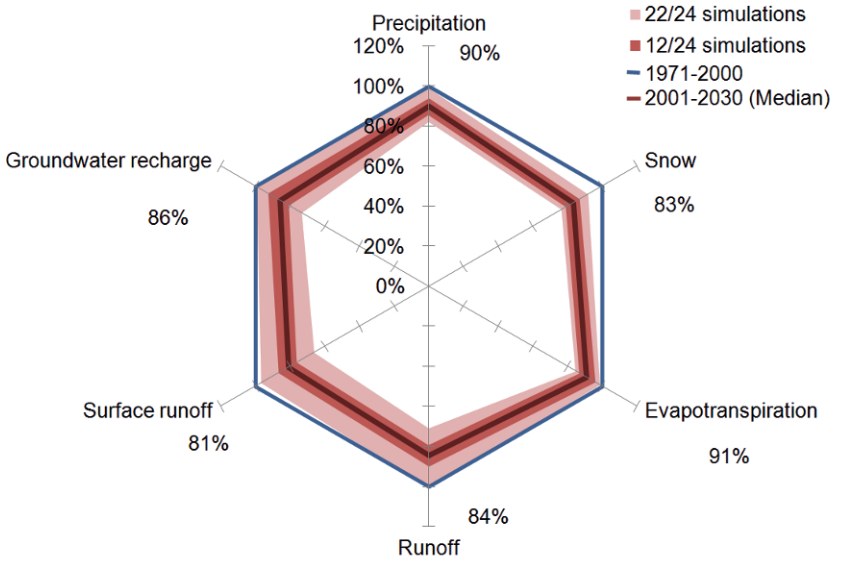

Fig. II-5.2.5: Development of annual water balance components in the Upper Drâa catchment under Climate Change (1971-2000 and 2001-2030), light red indicates the surrounding.

total uncertainty in scenario discharge can be attributed to the use of different ensembles, whereas the remaining 32% are due to the use of different downscaling techniques.

$$UCr_e = \frac{1}{e}\sum_{i=1}^{e}\max_j(\text{var}) \quad -\frac{1}{e}\sum_{i=1}^{e}\min_j(\text{var}) \quad j = 1..d$$
$$UCr_d = \frac{1}{d}\sum_{i=1}^{d}\max_j(\text{var}) \quad -\frac{1}{d}\sum_{i=1}^{d}\min_j(\text{var}) \quad j = 1..e \qquad \textbf{(eq. II-5.2.1)}$$

in which

e	=	number of ensemble runs
d	=	number of downscaling methods
UCr_e	=	absolute range of ensemble uncertainty in the result
UCr_d	=	absolute range of ensemble uncertainty in the result depending on the downscaling approach
var	=	variable considered

The unit depends on the unit of the variable.

5

Hydraa: A Spatial Decision Support System for water-related issues

Developing Spatial Decision Support Systems (SDSS) to promulgate research findings to stakeholders is one of the objectives of the IMPETUS approach (see chap. II-2). Using a SDSS, stakeholders who have little experience in hydrologic modeling can access model results and perform analyses of predefined or user-defined scenarios. The effects of mid- to long-term changes in the system (management or climate) can be assessed.

Within the Hydraa SDSS (Hydrologic Model for the Drâa catchment), the loose coupling of the SWAT and Cropwat models (Allen et al. 1998) is realized. As outlined in section I-6.2, these models calculate water availability and agricultural water demand within the Upper Drâa catchment. The results are contrasted, and unmet water demand can be determined for selected periods and locations. Using a Graphical User Interface, the user can easily assess the effects of Climate Change by using IMPETUS Climate Change scenarios or by creating their own climate scenarios. The latter can be used for sensitivity analysis or the incorporation of updated Climate Change projections. Furthermore, the effects of different management options can be assessed by altering the crop mix or areal extent of each oasis. Moreover, the SDSS enables the user to plot maps and time series of different water balance components. The outputs can be used for visualization or further processing in subsequent applications.

II-5.2.4 Scenario calculations for groundwater resources in the Middle Drâa valley using the IWEGS SDSS

Scenarios of the probable future development of groundwater availability and soil salinization in the Middle Drâa valley are assessed with the groundwater budget model BIL (Bilan des eaux souterraines) and the soil salinity model SahysMod (Spatial agro-hydro-salinity and groundwater model; see sect. I-6.2; ILRI 2005). The scenario calculations are based on climatic and socio-economic scenarios provided by IMPETUS (see chap. II-3; Paeth et al. 2005; Born et al. 2008). All scenarios are assessed for a period of 30 years (2001 – 2030) and compared with a baseline model run as a reference period (1974 – 2000, see sect. I-6.2). By incorporating BIL and SahysMod, the IWEGS SDSS (Impact on Water Exploitation on Groundwater and Soil) is developed to support conjunctive regional planning in the water sector. With IWEGS, the user can combine socio-economic scenarios with the preprocessed climatic scenarios of IMPETUS.

The IWEGS SDSS

The spatial decision support system IWEGS (Impact of Water Exploitation on Groundwater and Soil) combines groundwater budget assessment with soil salinity modeling. The model SahysMod is therefore coupled to the groundwater budget model BIL (ILRI 2005; IMPETUS 2006; Laudien et al. 2008; see subsect. I-6.2.4). The coupling also includes tools for preprocessing domestic water consumption and crop water demand, which are important components of the groundwater balance (see fig. II-5.2.6). IWEGS is used to evaluate the need of further investigations on groundwater and soil at the scale of the six Drâa oases in the Middle Drâa valley. If the model results reveal a relatively strong impact from Climate Change, for example, the oasis should be targeted by detailed surveying. IWEGS can estimate long-term changes in groundwater availability and soil salinity. The output of IWEGS is the lumped annual filling level of the aquifers beneath each oasis. The soil salinity is given as lumped annual electric conductivity (in the saturation paste) for each oasis. IWEGS is also capable of calculating socio-economic scenarios. The below described climatic scenarios are preprocessed. They can be selected to assess combined scenarios of Climate Change and socio-economic development. Thus, the user can adjust the population growth, cropping area, crop compilation, stream flow distribution for irrigation purposes and the irrigation efficiency for each oasis separately. These parameters are response indicators applied to manage the resources. Technical details concerning the IWEGS SDSS are given in subsection II-2.4.2.

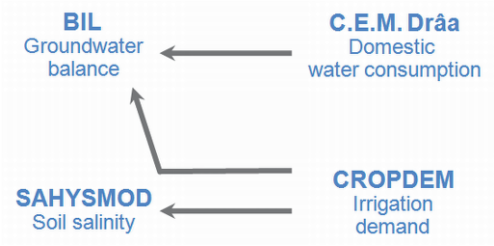

Fig. II-5.2.6: Principal of the model coupling in the IWEGS SDSS.

Climatic scenarios

The climatic scenarios for the groundwater resources of the Middle Drâa valley are derived from the REMO modeling of Climate Change (IMPETUS 2006; Born et al. 2008; Paeth et al. 2009). Available stream flow and regional precipitation determine the scenario projections.

Because water availability in the Middle Drâa valley is strongly dependent on the filling level of the Mansour Eddahbi reservoir (see sect. I-6.2), annual stream flow is derived from the hydrological modeling in the Upper Drâa catchment (see sect. I-6.2 and before). Consequently, all 24 scenarios of discharge to the Mansour Eddahbi reservoir simulated using the Hydraa SDSS (see before) are used to estimate the annual water availability for the Middle Drâa valley.

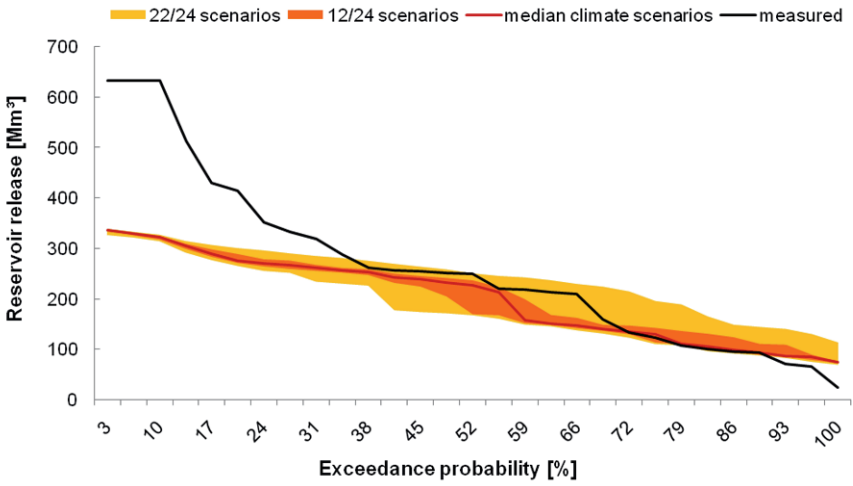

Fig. II-5.2.7: Future development (2001-2030) of the amount of water releases from the reservoir following the climate change scenarios simulated with the Hydraa SDSS (see before) compared to the period of the baseline model run (measured).

The climate scenarios suppose a substantial decrease in water released from the reservoir (see fig. II-5.2.7). The mean annual outflow in the period 2001 to 2030 is simulated to be 32 Mm³ less than in the period 1974 to 2000. Therefore, extraordinarily high releases are expected to decrease, whereas periods with extremely low release amounts will increase. This corresponds to the analysis of the REMO results, which show a higher frequency of drought periods (see sect. II-3.2).

Socio-economic scenarios

Three socio-economic scenarios are presented in this study based on the story lines of probable future development of the Drâa region (IMPETUS 2006; see sect. II-3.3). The three scenarios are marginalization (M1), rural development (M2) and business as usual (M3). In all three scenarios, response indicators are applied to project the story lines. The quantification of the response indicators represents the assumptions. Thus, the scenarios cannot be taken as prognoses, but they are used to test possible reactions to changes in the system.

The marginalization scenario (M1; see sect. II-3.3; IMPETUS 2006) uses water consumption as a response indicator for increasing migration and water pricing. Thus, domestic water consumption is assumed to decrease by 10%. At the same time, cropping intensity stays low and agricultural water consumption remains the same as in the baseline model run.

The rural development scenario (M2; see sect. II-3.3; IMPETUS 2006) considers the growth of tourism and decreasing migration as resulting in increased domestic water consumption. Accordingly, the domestic water use in rural areas is assumed to rise by 20% and in urban areas by 40%. In the baseline model run, the cropping area is adapted to surface water availability. Cropland is thus reduced in dry years and reaches its maxima after wet years. In this scenario, the cropping area has to be preserved at 70% of the maximum extent of the arable land to feed the inhabitants. Drip irrigation is simultaneously implemented to save water. It is included by improving the irrigation efficiency by 20%. The successive implementation follows a linear trend. Thus, drip irrigation is applied to 50% of the cropping area after 30 years.

The business as usual scenario (M3; see sect. II-3.3; IMPETUS 2006) takes into account population growth and urbanization as linear trends. Consequently, the domestic water consumption is assumed to develop according to the number of inhabitants. If population increases, the cropping area is assumed not to fall below 50% of the maximum of the arable land to assure subsistence agriculture in the Middle Drâa valley.

Results of climatic scenarios

As a consequence of hydrogeological heterogeneity, the aquifers react differently depending on the modified boundary conditions (see fig. II-5.2.8). Furthermore, the steep climatic and altitudinal gradient along the oasis chain of the Drâa has an impact. Thus, the global view of the results relating to the entire Middle Drâa valley is skewed concerning the water balance components for all model runs. Accordingly, the aquifers are evaluated separately for the interpretation of the scenarios, and exemplary phenomena of selected oases are presented.

The Mezguita, Ktaoua and Mhamid aquifers (see fig. I-3.2.3) are affected by significantly reduced groundwater availability. For Tinzouline, Ternata and Fezouata, the signal of Climate Change is not as clear as for the other three aquifers. The strongest influence of Climate Change is observed for very high and very

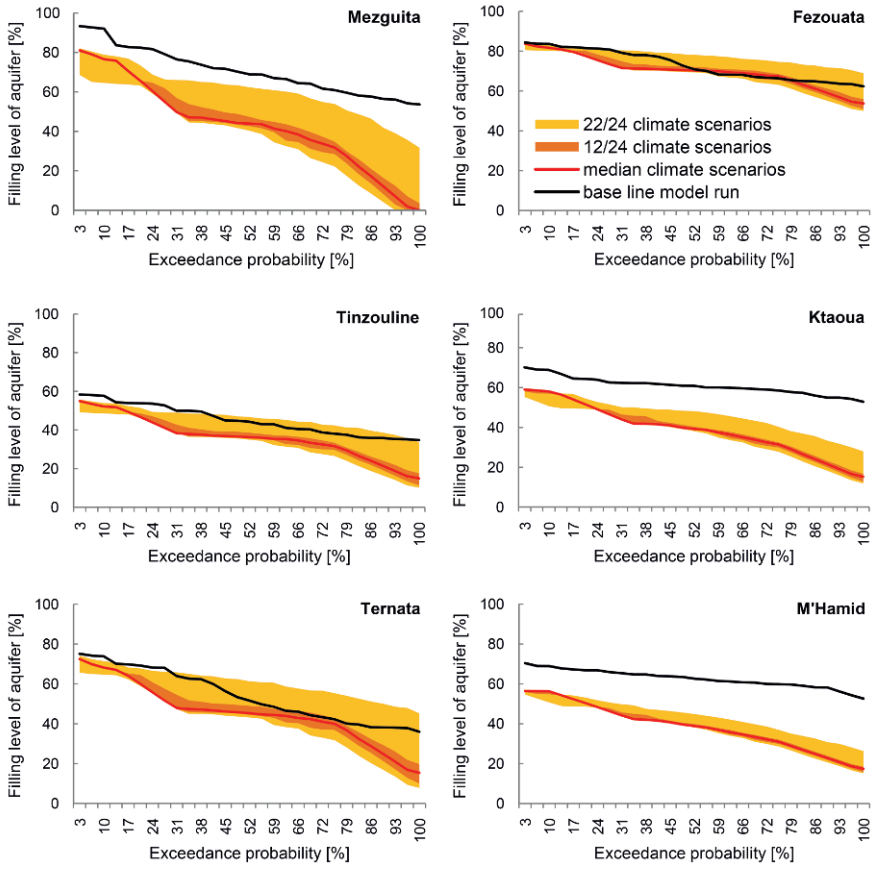

Fig. II-5.2.8: Results of Climate Change scenarios (2001-2030) compared to the baseline model run (for Mezguita, Tinzouline and Ternata (left column) and Fezouata, Ktaoua and Mhamid (right column).

low filling levels of the aquifers (see fig. II-5.2.8). Groundwater availability will be reduced under very wet conditions, assuming Climate Change in comparison to the baseline model run. This phenomenon is caused by the reduced surface water availability from the upstream Mansour Eddahbi reservoir (see fig. II-5.2.7). In very dry years, the groundwater availability is diminished because the buffer function of the aquifers against drought conditions is depleted relative to the baseline model run.

Soil salinity in 2030 is assessed to be higher for all oases under Climate Change conditions than under the recent climate following the SahysMod simulations (see fig. II-5.2.9). The Climate Change signal seems to be significant as the

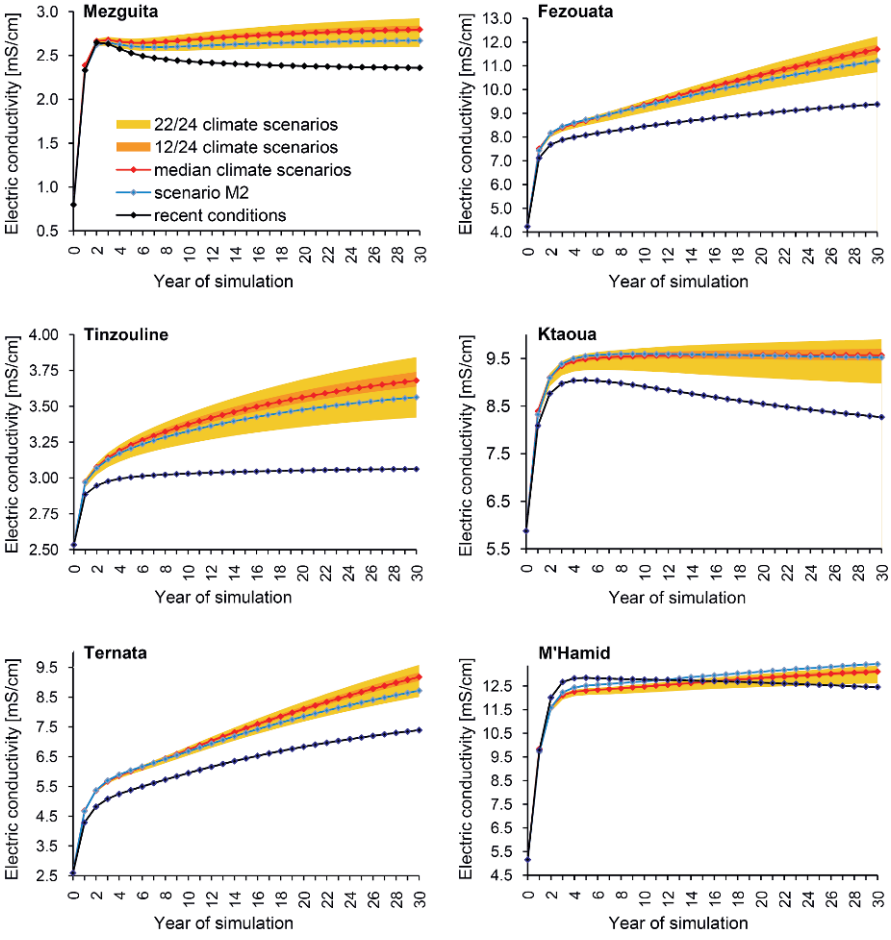

Fig. II-5.2.9: Results of climate and socio-economic change scenarios (2001-2030) for soil salinization compared to the baseline model run for the six Drâa oases (mind varying scaling for electric conductivity in this figure). The first two years must be regarded as a warm-up period for the SahysMod model.

uncertainty band originating from the different Climate Change scenarios does not superpose with the baseline simulation. Climate Change accounts for an increase in soil salinity of up to 5 mS/cm compared to recent climate conditions. The signal (difference to recent conditions) is strongest for Fezouata and lowest for M'Hamid. Groundwater salinity behaves in correspondence to soil salinity. The reason for the increase in salinity is the lower input of relatively low-saline surface irrigation water and, thus, an increased use of groundwater for irrigation purposes. Therefore, the transport of salts out of the rooting zone with the low-saline surface water is reduced. Additionally, the quality of the groundwater declines due to a lower input of percolating river water diluting the groundwater. Moreover, higher groundwater abstraction rates enhance this development.

Results of the socio-economic scenarios

The marginalization trend in the Middle Drâa valley results in a slight increase in groundwater availability, even at the regional scale (see fig. II-5.2.10). As mentioned in section I-6.2, groundwater extraction for drinking water supply has a great impact on the local water balance. As no changes considering agricultural practices are assumed in this scenario, changes in soil and groundwater salinity at the regional scale are negligible. Slight effects can only be expected at the local scale if the non-saline lateral afflux increases due to decreasing drinking water abstraction.

The rural development scenario shows that the groundwater reservoirs will run dry during the drought period, with the exception of Fezouata and M'Hamid. The implementation of drip irrigation saves water and mitigates the drought impact

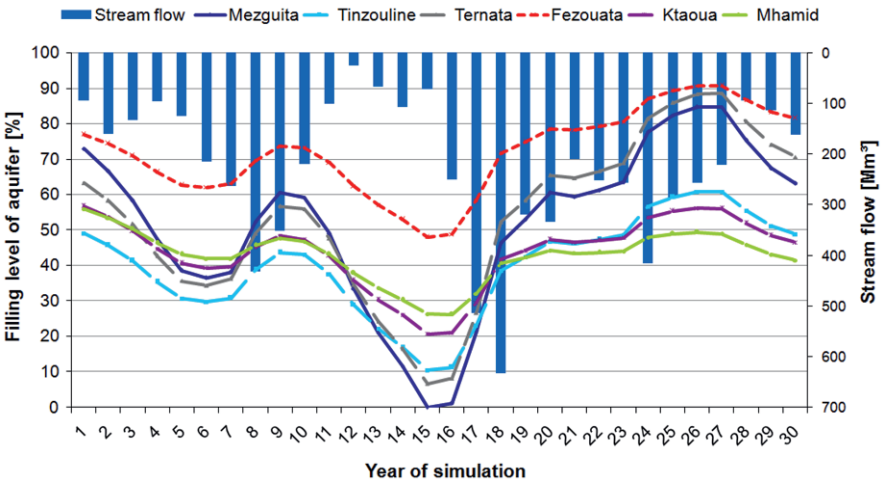

Fig. II-5.2.10: Scenario results of rural development (M2) for annual filling levels of aquifers with the stream flow of the Drâa over 30 years based on the climatic conditions during the base line model run.

concerning water availability. In Mezguita, however, it would not be sufficient to apply drip irrigation for 50% of the focused cropping area to avoid dry-out during a severe drought after 10 to 15 years of the scenario period (see fig. II-5.2.10). Further estimations show that if drip irrigation is applied to 60% of the cropping area, the groundwater reservoir could be preserved. In comparison to the baseline model run, the regional recharge becomes more important relative to the total groundwater volume. The average value of regional recharge over the modeled period accounts for 0.4% of the total groundwater availability for the Middle Drâa valley and 1% in rural development scenario. In Mezguita, the average value of regional recharge increases from 0.7% to 2% of the total groundwater volume. In the entire Middle Drâa valley, the irrigation extractions from groundwater are reduced by 2% compared to the baseline model run. This is due to drip irrigation. The total recharge amount is diminished by 3% for the same reason. Although only a relatively low fraction of irrigation water is saved and a constant area is farmed, drip irrigation mitigates drought effects on the aquifers. This is another indication of the sensitivity of the system against management actions compared to climatic influences.

The application of drip irrigation leads to an increase in soil salinity compared to recent conditions (see fig. II-5.2.10). The signal is again strongest in Fezouata, but lowest in Mezguita. Nevertheless, its influence is nearly as high as the Climate Change impact for the five upper oases, and it is even stronger for M'Hamid. The reason for the increase is the diminished amount of irrigation water applied to the fields and thus the reduced transport of salts out of the rooting zone. This leads to an accumulation of salts in the soil (see fig. II-5.2.9). For the soil resource, then, the application of drip irrigation is not favorable, at least as long as no counteract-

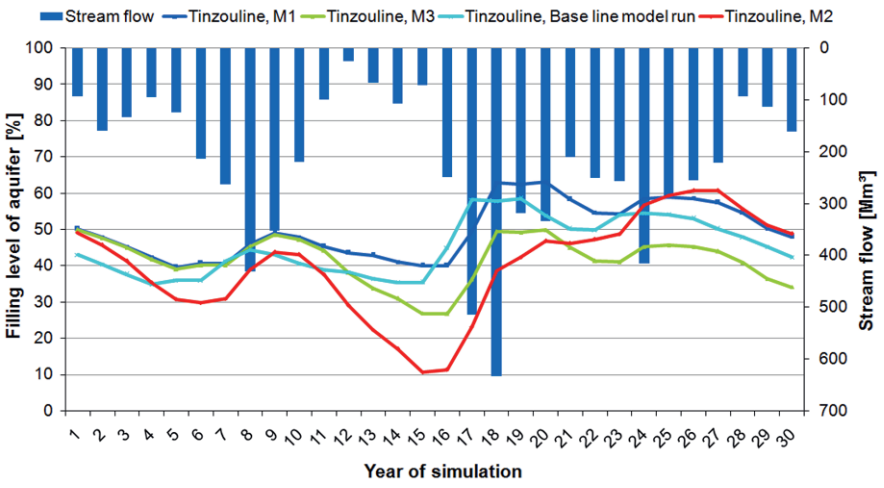

Fig. II-5.2.11: Scenario results of socio-economic changes (M1, M2, M3) over 30 years and the result of the baseline model run for the annual filling levels of the Tinzouline aquifer with the stream flow of the Drâa.

ing measures such as soil washing are carried out. Accordingly, drip irrigation affects groundwater and soil in opposite directions. Groundwater resources can be preserved while soil quality declines.

The business as usual scenario reveals decreasing groundwater availability due to increased domestic water consumption per capita in combination with population growth (see fig. II-5.2.11). Comparable to the marginalization scenario, no changes in agricultural behavior are expected in this scenario. Thus, the salinity of the soil and the aquifer is only affected at the local scale when the lateral afflux of non-saline water from the surrounding mountains is reduced due to higher drinking water extraction. However, this effect does not influence salinity at the regional scale.

II-5.2.5 Conclusions

According to the PRO-RES modeling results for the A1B scenario, the trend toward more extreme periods and to a slight decrease in the mean monthly inflow to the Mansour Eddahbi reservoir from 2011 to 2020 would lead to reduced water availability and, therefore, a higher water management demand. Low inflow volumes to the reservoir lead to decreased water releases toward the Middle Drâa valley. Water demands for agriculture and drinking water would not be met, as is the case in the last years. Thus, an increase in groundwater extraction is expected (see subsect. II-5.2.4).

Several ways of using regional climate model outputs have been investigated to create climate scenarios characterizing changes in mean climate for the semi-arid, mountainous Upper Drâa catchment. Different downscaling methodologies have been developed and compared. Despite their different characteristics, the resulting range in results is narrow. The effect of different ensemble members is larger than the effects of the downscaling techniques. Therefore, general trends in discharge behavior can be identified. A general decline in surface water availability can be stated, but there is no particular trend for extreme dry or wet periods. Due to the operational scale of the SWAT model (daily time steps, point scale climate data), changes in the inter-annual variability of precipitation could not be accounted for. Since model biases considering precipitation outrange Climate Change signals, the use of different Climate Change projections (global or regional) could prove helpful. Furthermore, a large variety of agricultural measures can affect water availability in the Upper Drâa catchment in the future. To assess their effects on the catchment's water balance, the Hydraa SDSS has been developed.

Interdisciplinary studies on the influence of water use on groundwater and soil resources in the Middle Drâa valley led to a model-based system analysis and the development of the IWEGS SDSS (see sect. I-6.2). Scenario analyses of climatic and socio-economic changes reveal significant impacts on groundwater availability and soil salinity. Climate Change will lead to enhanced water scarcity and soil

degradation. Even more, changes in water use strategies will influence the resources. Thus, adapted measures can mitigate drought effects. Because water saving measures such as drip irrigation can be neutralized by salinization effects, integrated research is the most promising base for resources management.

References

Allen, RG, Pereira LS, Raes S, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Papers 56. FAO, Rome

Arnell NW, Hudson DA, Jones RG (2003) Climate change scenarios from a regional climate model: Estimating change in runoff in southern Africa. http://www.agu.org/pubs/crossref/2003/2002JD002782.shtml Accessed 27 February 2009

Arnold JG, Allen PM, Bernhardt G (1993) A Comprehensive Surface-Groundwater Flow Model. J Hydrol 142(1-4):47-69

Born K, Fink A, Paeth H (2008) Dry and wet periods in the northwestern Maghreb for present day and future climate conditions. Meteorol Z 17:533-551

Ministère des travaux publics (ed) (1998) Etude du plan directeur de l'aménagement des eaux des bassins sud-atlasiques, Mission 3: Etude des schemas d'aménagement. Vol. 4. Rabat

Martinec J (1975) Snowmelt-Runoff model for stream flow forecasts. Nord Hydrol 6(3):145-154.

Paeth H, Born K, Girmes R, Podzun R, Jacob D (2009) Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes. J Climate 22(1):114-132

Paeth H, Born K, Podzun R, Jacob D (2005) Regional dynamical downscaling over Westafrica: model evaluation and comparison of wet and dry years. Meteorol Z 14:249-267

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

ILRI (2005) SahysMod – Descriptions of Principles, User Manual and case studies – Version 1.7. http://www.waterlog.info/pdf/sahysmod.pdf. Accessed 15 June 2009

IMPETUS (2006) Second Final Report –1.5.2003 – 31.7.2007. University of Cologne and Bonn. http://www.impetus.uni-koeln.de/content/download/EB2006/FinalReport2003_2006.pdf. Accessed 8 October 2009

Laudien R, Klose S, Klose A, Rademacher C, Brocks S (2008) Implementation of non-Java based interfaces to embed existing models in Spatial Decision Support Systems - Case study: Integration of MS® Excel-models in IWEGS. In: Chen J, Jiang J, Kainz W (eds) Proceedings XXXVII, Part B2, Commission II, ISPRS Congress, 3-11 July 2008, Beijing

II-5.3 Land use and land cover in Southern Morocco: Managing unpredictable resources and extreme events

A. Linstädter, G. Baumann, K. Born, B. Diekkrüger, P. Fritzsche, H. Kirscht, and A. Klose

Abstract

In arid environments, water is a highly unpredictable natural resource. Land use must be adapted to the availability of water for plant growth and as drinking water. In the oases along the river Drâa, the variability of available water is partly buffered by natural storage and by human management. The vast areas outside the oases are used as rangelands. Here, water resources can only be managed indirectly, through the management of the vegetation and natural resources, firewood and forage. To understand the effects of direct and indirect water resource management on the social-ecological system's functioning, local land use strategies must be analyzed. In the past, research has concentrated on the management of water resource scarcity because this is an obvious problem of natural resource management in arid regions. In this section, we apply a broadened approach and analyze the relevant factors on an annual and inter-annual scale. We identify key traits of pastoral land management in the High Atlas region that mitigate the negative effects of extreme weather events (droughts and floods) and slow down land degradation. Our results show that local land use mitigates drought effects through a preventive natural resource management, particularly in times of abundant rainfall; it maintains or increases the capacity of the rangeland vegetation to buffer against rainfall variability.

Keywords: Ecological buffers, erosion, floods, drought, pastoralism, range management, resource reliability, severe rainfall

II-5.3.1 Introduction

Growing human populations living in drylands, and global Climate Change increase the land use pressure (Meze-Hausken 2000). Unsustainable forms of land use lead to land degradation, which is manifested by a declining soil fertility, increasing erosion, deforestation, and the loss of biodiversity (Eswaran et al. 2001;

see sect. I-2.2). Ultimately, land degradation leads to a reduction or loss of the biological or economic productivity of the land. Thus, it increases the vulnerability of local populations who depend on these systems for their livelihoods. Given the number of people affected by the problem, land degradation is ranked as one of the most severe environmental problems today. The debate on land degradation is, however, relatively polarized, particularly for sub-Saharan Africa (Prince et al. 1998; Dougill et al. 1999; Olsson et al. 2005) and for the Western Mediterranean (Martínez-Fernández and Esteve 2005; Carrión et al. 2009). Vividly discussed are the spatial extent and severity of degradation (Hary et al. 1996; Behnke and Abel 1996) and its causes and effects (Dahlberg 2000; Hein 2006; Retzer 2006; Gillson and Hoffman 2007; Hambler et al. 2007). Recent estimations state that land degradation affects about 20% of global drylands (Millennium Ecosystem Assessment 2005). One of the outcomes of the degradation process is a reduced capacity of the degraded environments to handle disturbances, such as droughts and floods (Rockström 2003). Climate Change projections indicate an increased variability of rainfall in north-western Africa (see sect. I-5.2), which is accompanied by a higher frequency of extreme daily events in High Atlas mountain regions (see fig. I-5.2.1). Thus, land use practices in Morocco's Drâa region must cope with these substantial changes in the coming decades.

In the oases of the Drâa catchment, a high spatio-temporal variability of precipitation is partly buffered by natural storage and by human management (see sect. II-5.2). The vast areas outside the oases are used as rangelands. Here, water resources and their variability can only be managed indirectly through the management of the vegetation and its natural resources, fuel wood and forage. To understand effects of direct and indirect water resource management on the social-ecological system's functioning and resilience, local land use strategies must be analyzed. In the past, research has concentrated on the management of water resource scarcity because this is an obvious problem of resource management in arid regions. Within the context of IMPETUS, we apply a broadened approach and analyze the relevant factors on an annual and inter-annual scale. We aim to identify key traits of pastoral land management (such as local mobility decisions) that slow down the land degradation and mitigate the negative effects of extreme weather events in the Drâa region.

II-5.3.2 Too much rain: The case of severe rainfall events

Positive rainfall anomalies yield abundant water resources. After an abundant rainfall, the available water allows high plant productivity on pastures and in agricultural areas. However, if large amounts of rainfall occur during a short period of time, the resulting severe rainfall may cause considerable damage to environmental and agricultural resources. We used an extreme value analysis applied to the scenario output of nested climate models to predict changes in the frequency of days

with severe rainfall for the Drâa region (Paeth et al. 2009). Ensemble runs allowed the construction of rainfall time series from 1960-2050 for northern Africa (see fig. II-5.3.1). Further regionalization was performed by a multi-linear regression with elevation and exposition. The return values were estimated by a peak-over-threshold analysis (POT), and the fit of a Generalized Pareto Distribution (GPD) to the rainfall distribution above a critical limit was obtained from an objective analysis (Born et al. 2008).

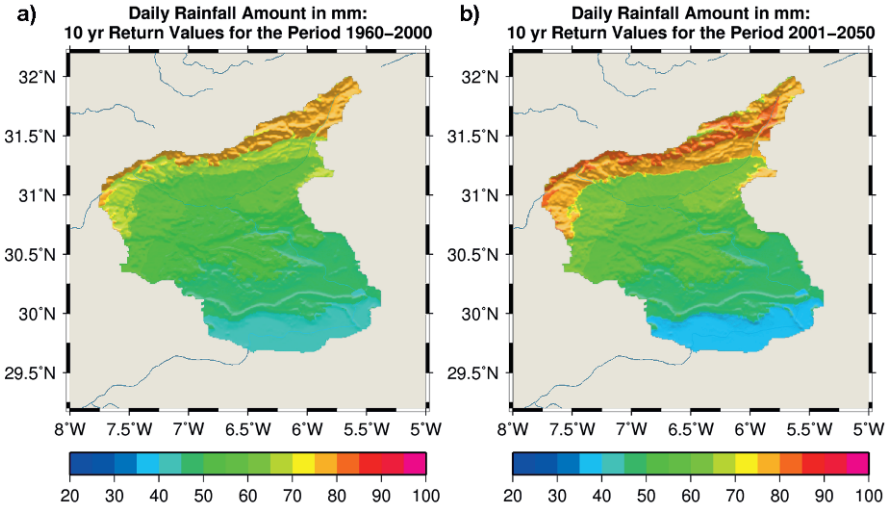

Fig. II-5.3.1: The ten-year return values of the daily rainfall from regional climate model (REMO) runs. The present-day (a) vs. future (SRES A1B) scenario conditions (b) are shown.

The return values of 10-year recurrence events, i.e., the maximum daily rainfall that is expected to recur every ten years, show a slight decrease in the southern arid regions, but shows an increase in those parts of the upper Drâa catchment that contribute to the barrage El Mansour Eddahbi. Although the annual mean rainfall is expected to decrease slightly and the occurrence of dry periods is expected to become more frequent, the frequency of the extreme rainfall events may increase under future climate conditions.

The effects of severe rainfall: Floods and erosion

The negative effects of severe rainfall events in Morocco are floods and soil erosion by water (Linstädter and Zielhofer 2010). Severe rainfalls may trigger extreme erosion rates in this region; the area has a high vulnerability towards erosion due to high relief energy, shallow soils featuring low organic matter contents and a sparse vegetation, which is further reduced by overgrazing. In this study, the erosion

risk is estimated by applying the PESERA (Pan European Soil Erosion Risk Assessment) model, which explicitly considers rainfall and soil patterns, as well as the vegetation cover (see sect. I-6.2). Based on the PESERA model, the SDSS SEDRAA (the estimation of the soil erosion risk in the Drâa region) was developed (see fig. II-5.3.2). Using SEDRAA and regionalized climate projections derived from IPCC climate scenarios A1B and B1 by application of the IMPETUS statistico-dynamical downscaling method (see subsect. II-3.2.6), the erosion risk was simulated under the scenarios of Climate Change. The user is able to choose a climate scenario and simulation period for the measured climate data and to alter the land use in two different ways. He can either choose the regions through a criteria query, e.g., alter the land use in the regions with less than a 10° slope inclination, or through a graphic choice. In the latter case, the user can draw polygons where the land use is to be changed on-screen. The possible land use changes include changing the vegetation type, e.g., from steppe to forest for the simulation of afforestation, or using pastoral land management by defining a reduced impact of the vegetation by grazing.

The SEDRAA results concerning the impact of Climate Change following the IPCC SRES scenarios A1B and B1 (see sect. II-3.2) and the effect of socio-eco-

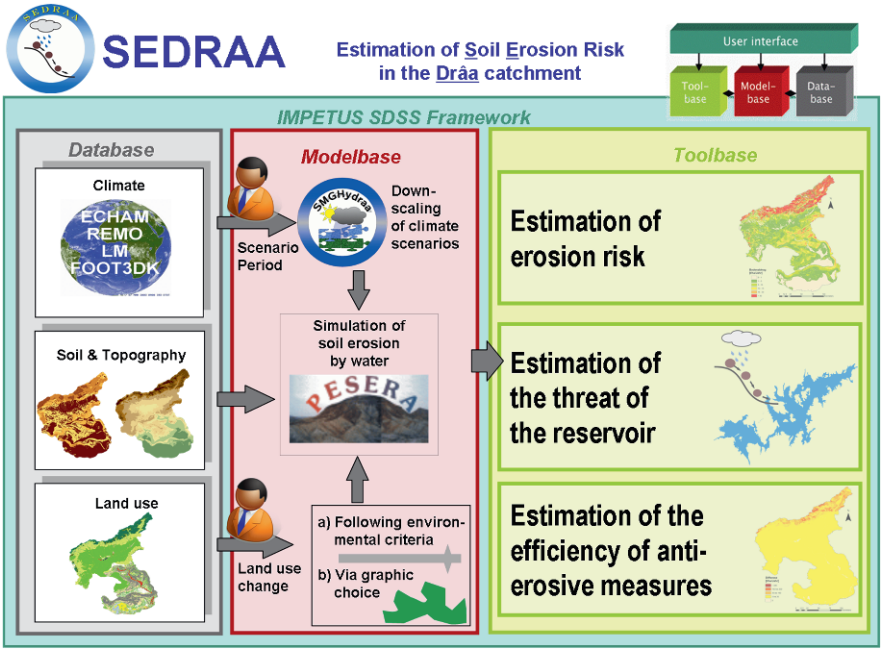

Fig. II-5.3.2: The general workflow of the SDSS SEDRAA. The erosion risk model PESERA is driven by climate, soil, topography and land-use data. The effect of the management options on the amount and spatial variability of the erosion rates can be studied by analyzing different scenarios.

nomic change following the IMPETUS scenarios for the Drâa catchment (see sect. II-3.3) are presented below. Finally, simulations of the combined climate and socio-economic change scenarios are displayed.

Because PESERA calculates the mean long-term erosion rates for climatic periods, the climate data are subdivided into four periods of 15 years each (2005-2020, 2015-2030, 2025-2040, and 2035-2050). The results of the scenarios are compared to the reference period, 1960-2000. The standard deviation values given below belong to the six ensemble runs. The downscaled climate scenarios (see above) indicate a rise in the temperature by 1.4 ± 0.3°C and a decrease in the precipitation by 30 ± 11 mm for the Drâa catchment up to 2050 (see fig. II-5.3.3). Using the modeled climate data for the PESERA model runs leads to an increase in the erosion up to 2050 compared to the reference period (see fig. II-5.3.4). The mean erosion rate over the whole catchment increases by 21 ± 17 % in the period from 2035-2050 compared to the past (1960-2000) but shows a high spatial variability. A maximum increase of 31 ± 12 % is estimated for the period of 2025-2040. As both the total precipitation and the number of rainy days will decrease during this time (see above), the mean precipitation per rainy days stays nearly constant (see fig. II-5.3.3). However, this condition only holds true for the mean values because the variability of the rainfall events, and particularly the frequency of extreme events, will substantially increase over the time period used (see fig. II-5.3.1).

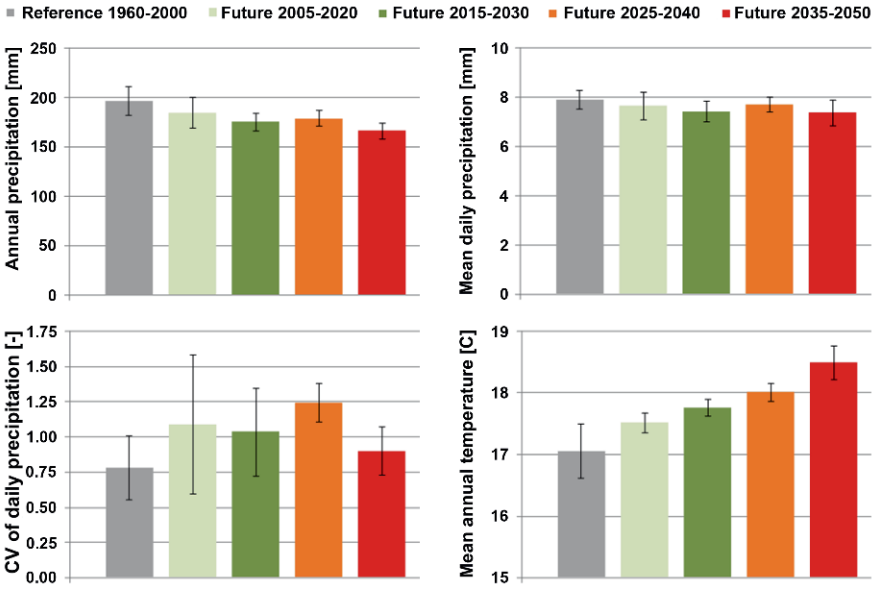

Fig. II-5.3.3: The trends of the IPCC SRES climate scenarios A1B and B1 compared to the reference period, 1960-2000 as calculated by REMO. CV = coefficient of variation. Error bars: the standard deviation from ensemble runs.

The higher temperatures together with the reduced precipitation lead to reduced plant cover. This degradation of the vegetation triggers a reduction of organic matter in the soils and subsequently leads to a reduction of the soil water storage. This reduced soil water storage leads to an increase in runoff. The higher variability of precipitation events will additionally increase the surface runoff. The variability of the daily precipitation is highest in the period of 2025-2040, corresponding to the highest erosion rates in this period. Thus, the higher erosion rates are a combined result of a sparser vegetation cover (reduced through a higher temperature and less precipitation) and more frequent events of severe rainfall.

Mitigating floods and erosion: The effects of pastoral land management

Land management can either intensify or mitigate the negative effects of severe rainfall (Rowntree et al. 2004). Here, we aim to quantify the impact of changing human land use activities on soil erosion rates using the IMPETUS socio-economic scenario approach (see sect. II-3.3). Neither changes in land use, such as an expansion of the agricultural area, nor direct measures of erosion control, such as afforestation efforts, can be explicitly considered in these scenarios. Thus, we concentrate on the changes in range management and the changes in firewood extraction, and we connect them to specific scenarios. As vegetation recovery is a slow process, vegetation dynamics are, in analogy to the climate periods, considered in four subsequent time steps.

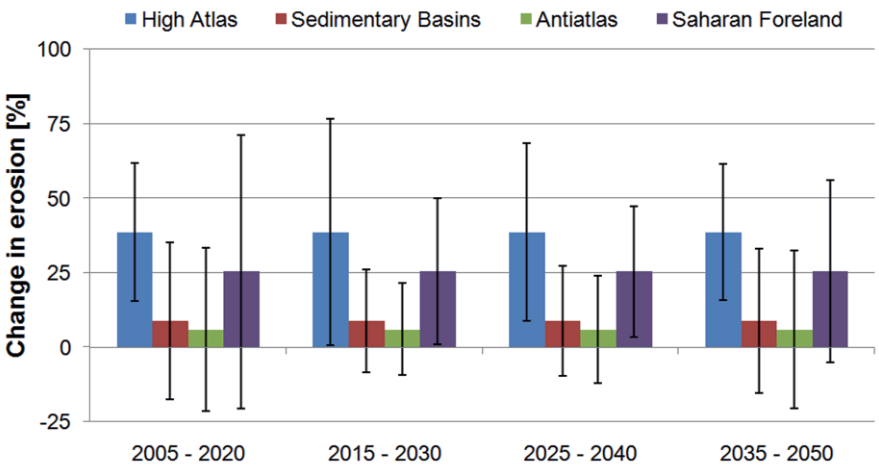

Fig. II-5.3.4: The percent change in the erosion rate compared to the reference period, 1960-2000, in four different regions in the Drâa catchment as calculated by PESERA. Error bars: the standard deviation from ensemble runs.

Table II-5.3.1: The definition of the IMPETUS socio-economic scenarios for erosion risk assessment. BOZZ = Basin of Ouarzazate. Each time step refers to one climatic period.

Time step	Scenario M1	Scenario M2
1 (2005-2020)	Extraction of 10% firewood in a 2 km radius around villages	-10 % vegetation reduction in the High Atlas and South, +10 % vegetation reduction in the BOZZ
2 (2015-2030)	Extraction of 20% firewood in a 2 km radius around villages	-20 % vegetation reduction in the High Atlas and South, +20 % vegetation reduction in the BOZZ
3 (2025-2040)	Extraction of 20% firewood in a 5 km radius around villages	-30 % vegetation reduction in the High Atlas and South, +30 % vegetation reduction in the BOZZ
4 (2035-2050)	Extraction of 13% firewood in a 5 km radius around villages	-40 % vegetation reduction in the High Atlas and South, +40 % vegetation reduction in the BOZZ

In scenario M1, *Marginalization*, the number of animals in the catchment is presumed to stay constant. Due to rising energy costs, the firewood extraction increases, leading to a higher degradation of the vegetation close to villages (see table II-5.3.1). In scenario M2, *Rural development*, the livestock numbers are assumed to decrease in the rural areas of the IMPETUS scenario regions, the 'High Atlas' and 'South', because fewer people follow a nomadic lifestyle. In contrast, animal numbers increase in the 'Basin of Ouarzazate' region due to its vicinity to markets. Hence, the vegetation degradation is presumed to increase in the Basin of Ouarzazate and to decrease in the High Atlas and the south (see table II-5.3.1). In scenario M3, *Business as usual*, no changes in the animal numbers and firewood extraction are assumed.

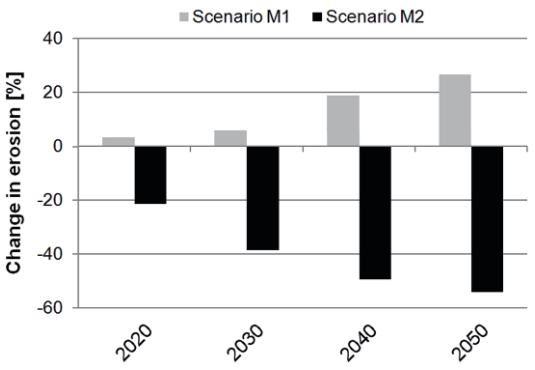

Fig. II-5.3.5: The change in the mean annual erosion rate compared to the baseline scenario in the whole Drâa catchment considering the IMPETUS socio-economic scenarios M1 and M2 under recent climate conditions as calculated by PESERA.

The assumptions in scenario M1, *Marginalization*, lead to a 27% increase in mean soil erosion in the whole catchment area (see fig. II-5.3.5). This increase at first appears substantial; however, remember that 55% of the catchments surface lies within a 5 km radius around villages (see fig. II-5.3.6, left). Regarding scenario M2, *Rural development*, the simulation leads to a reduction of the mean

erosion rate by 54% (see fig. II-5.3.5). The grazing pressure is reduced by 73% of the catchment's surface. Thus, the protection of vegetation in the mountainous zones of the High Atlas and Antiatlas reduces the mean erosion rate in the catchment sufficiently to outbalance the increase in grazing pressure and thus erosion in the Basin of Ouarzazate (see fig. II-5.3.6, right).

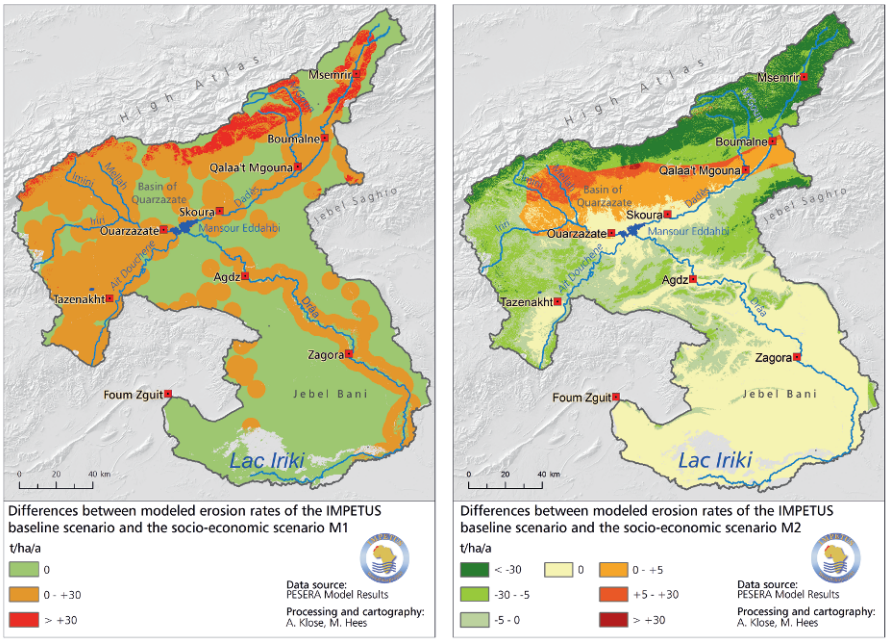

Fig. II-5.3.6: Differences between the modeled erosion rates of the IMPETUS baseline scenario and the socio-economic scenarios M1 (left) and M2 (right) as calculated by PESERA.

The combined impact of climate and land use change on soil erosion

In a next step, the scenarios of climate and land use change are jointly simulated to assess their combined impact on the soil erosion rates in the Drâa catchment (i.e. the impact of Global Change in this region). The results are compared to the reference period, 1960-2000, and to the future climate without land use changes. If the Climate Change impact is combined with the *Marginalization* scenario, a further aggravation of the erosion problem due to human impact occurs (see fig. II-5.3.7). High energy costs force the inhabitants to increasingly use woody plant material (including shrubs and sub-shrubs) as an energy source. Together with the higher probability of severe rainfall events, this increased use of woody plants leads to an increase in erosion of 64% until 2050. The separate Climate Change effect accounts for a surplus of 25%, and thus the human impact exceeds the cli-

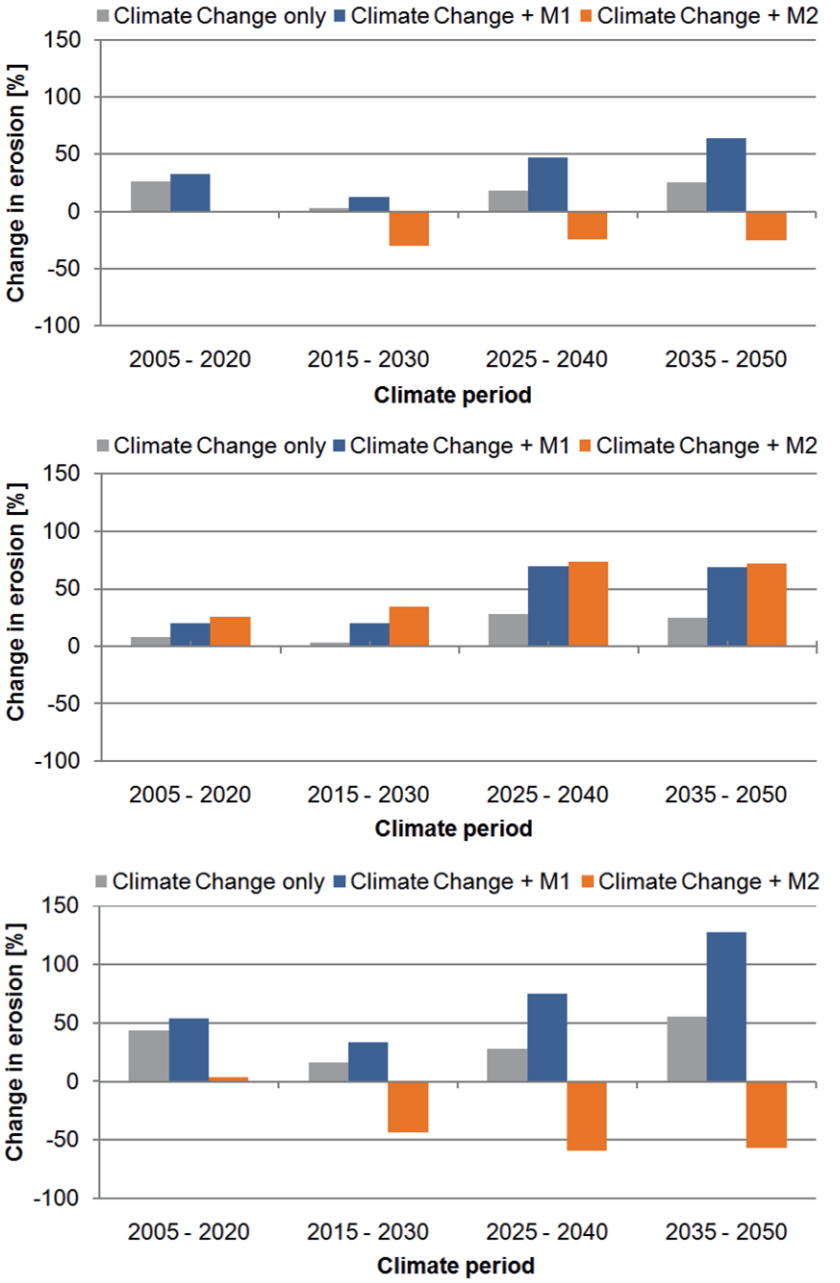

Fig. II-5.3.7: The results of the combined climate change and socio-economic scenarios compared to the reference climate period and the climate change only scenario as calculated by PESERA. Top: The whole Drâa catchment; middle: The Basin of Ouarzazate; bottom: The High Atlas.

matic impact. For scenario M2, *Rural development*, combined with the Climate Change scenario, the model simulates a reduction of erosion of 25% compared to the reference period (see fig. II-5.3.7, top). Comparing the combined simulation with the Climate Change effect, the human impact reduces erosion rates by 50%. Hence, an abandonment of the pastoral-nomadic lifestyle, which leads to a decreased grazing pressure in rural areas, compensates for the Climate Change effect on the soil erosion rates. However, this effect shows a strong spatial variation within the catchment. In the Basin of Ouarzazate, a higher grazing pressure increases the erosion rates (see fig. II-5.3.7, middle), whereas in the High Atlas, the livestock numbers are reduced. Consequently, erosion strongly declines (see fig. II-5.3.7, bottom). Regarding the whole Drâa catchment, the human influence assumed in scenario M2 will outweigh the negative impact of Climate Change.

Our study indicates an accelerated erosion due to the effects of Climate Change. Although the mean annual precipitation is predicted to decrease, higher erosion rates will occur because of reduced protective vegetation cover and higher rainfall variability. Range management is potentially able to outweigh the negative effects of Climate Change when rural development in the Drâa catchment is assumed; it could also aggravate the problem if further marginalization took place. Thus, range management has a strong impact on the future erosion risk and may serve as an anti-erosive measure.

II-5.3.3 Too little rain: The case of meteorological drought

Negative rainfall anomalies are an indication of low rainfall. They lead to a shortage of water with the extreme event of a meteorological drought. A meteorological drought can be detected with the aid of the Standardized Precipitation Index (SPI). The SPI is a standard drought analysis tool (McKee et al. 1993) based on the assumption that rainfall amounts can be represented by gamma distributions. An index of rainfall anomalies is calculated by transforming from the gamma to normal distribution using an equal probability method, so that the index values show nearly a Gaussian normal distribution. The unit of the SPI is in standard deviations of the normal distribution. The resulting SPI series inform about wet conditions (positive values) or dry conditions (negative values). The empirical limits for droughts are often defined by thresholds of -1.7 (drought) and -2.2 (extreme drought). Figure II-5.3.8 shows the SPI values from 1900 to 2050 from both observational data and climate models. The reference interval for which the SPI is calculated is 1961-2050.

SPI values show two important things. First, the future climate scenario (SRES A1B) indicates a remarkable and statistically significant shift towards more dry conditions. Second, extreme droughts tend to occur more frequently in the last thirty years of the climate simulation (Born et al. 2008). The occurrence of extremely low precipitation indices in this period is comparable to the second and third decade of the last century.

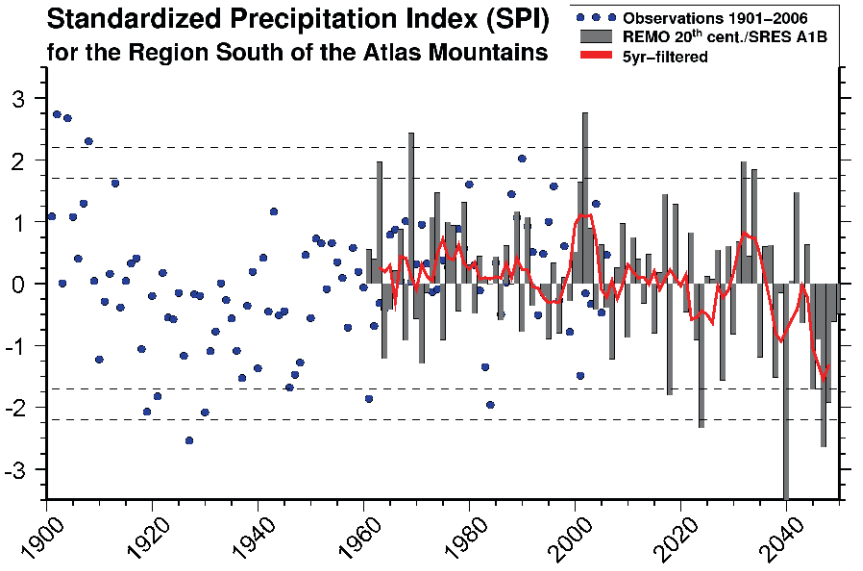

Fig. II-5.3.8: The Standardized Precipitation Index (SPI) from observations (dots) and regional climate model (REMO) data (bars and red line) for the region south of the Atlas Mountains.

Effects of meteorological drought: Natural resource scarcity

Drought is an ambiguous term, subject to human objectives and the weight of emphasis on meteorological, agricultural, hydrological or socio-economic dimensions (Thurow and Taylor 1999). A meteorological drought stands at the base of all drought definitions because it describes physical environmental changes. It is translatable to higher levels of natural resource scarcity. First, it translates to the level of available fodder or food in the case of an agronomic drought, when the soil moisture is depleted so that the yield of plants is reduced considerably. Second, it translates to the level of economic activities in the case of a socio-economic drought. The latter is 'a condition of moisture deficit sufficient to have an adverse effect on vegetation, animals and man over a sizeable area' (see the review of drought definitions in Agnew and Anderson 1992). From the point of land use objectives, a good definition of drought is 'when water availability drops below a certain threshold for a specific ecosystem service' (Agnew and Warren 1996) because it considers the impacts upon a land use system or society.

A socio-economic drought in rangelands is triggered by a scarcity of available forage. This scarcity depends on plant production, and on the storage of fodder on pastures. In the Drâa catchment, the amount of available fodder in relation to rainfall and grazing pressure is assessed following a nested design. Detailed information on the functional changes in the vegetation related to abiotic site conditions, such as climate and soil, and to the biotic site conditions, such as grazing pres-

sure, is recorded on a local scale with the methods of vegetation ecology. Experimental approaches like grazing exclosures are applied. They are extrapolated to larger spatial and temporal scales by means of remote sensing using time series analyses of the Normalized Difference Vegetation Index (NDVI) based on MODIS data from 2000-2008. In the next step, the data are connected to socio-economic information on range management strategies.

Mitigating drought: The role of ecological buffers

The effects of meteorological droughts in the Drâa catchment could, like in other drylands (Thurow and Taylor 1999; McAllister et al. 2006; Samuels et al. 2007), be mitigated by an adaptive range management as practiced by pastoralists. The management system has to cope with the temporal and spatial variabilities of natural resources (Linstädter and Bolten 2007), which are mainly driven by the rainfall variability. In this context, a drought is not an occasional catastrophe, but a risk inherent to the system to which pastoralist economies have adapted (Morton and Barton 2002). Our case study is the range management of the Ait Toumert pastoralists, a small Berber fraction that has its pastures on the southern slopes of the High Atlas Mountains (for more information on this case study, see sect. II-5.1 and subsect. II-5.4.3). Their normative transhumance cycle runs along a steep altitudinal gradient, which reflects a gradient of climatic aridity and rainfall variability (Baumann et al. 2008). Mountainous pastures are used during the summer months and lowland pastures are used during winter. The transition pastures in-between are grazed during some months in spring and autumn (see fig. II-5.3.9 and fig. II-5.4.3). The large winter pastures are characterized by a high spatial and temporal heterogeneity of natural resources; these measures are less variable in space and time on the smaller summer pastures (Kemmerling et al. 2009, personal communication).

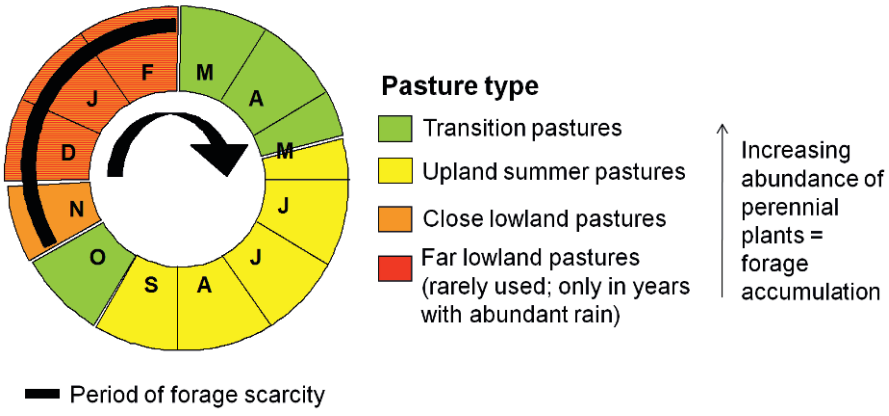

Fig. II-5.3.9: The annual transhumance cycle of the Ait Toumert pastoralists on their four pasture types, indicating the movements between pastures.

As plant-available water is the principal limiting resource for plant growth, variable rainfall may be translated to aboveground net primary production (ANPP) and to available forage, either in an amplified or in a buffered way (Linstädter 2009). Three ecological buffer mechanisms can occur. First, the ANPP variability may be abiotically (hydrologically) buffered on sites experiencing low aboveground and belowground water losses or sites having a water surplus due to lateral water transport. Second, ANPP variability can be biotically buffered by a high proportion and fitness of perennial plants (Müller et al. 2007b; Owen-Smith 2008). Range management can modulate the effects of this mechanism: while intensive and ill-timed grazing may result in a decline in the ANPP of perennial plants (Paruelo et al. 2008), moderate grazing may, like other moderate levels of disturbance, increase primary production due to positive effects on plant fitness (Milton et al. 2000; Zimmermann et al. 2010). We thus propose the variability of rain use efficiency (RUE) as a measure of how effectively the impact of rainfall variability on primary production is buffered by abiotic and biotic mechanisms (see fig. II-5.3.10). For livestock nutrition, the rainfall variability may also be buffered biotically by a natural fodder storage built up by perennial plants (Wiegand et al. 2004). This is the third buffering mechanism for rainfall variability (see fig. II-5.3.11), which can also be related to mobility decisions.

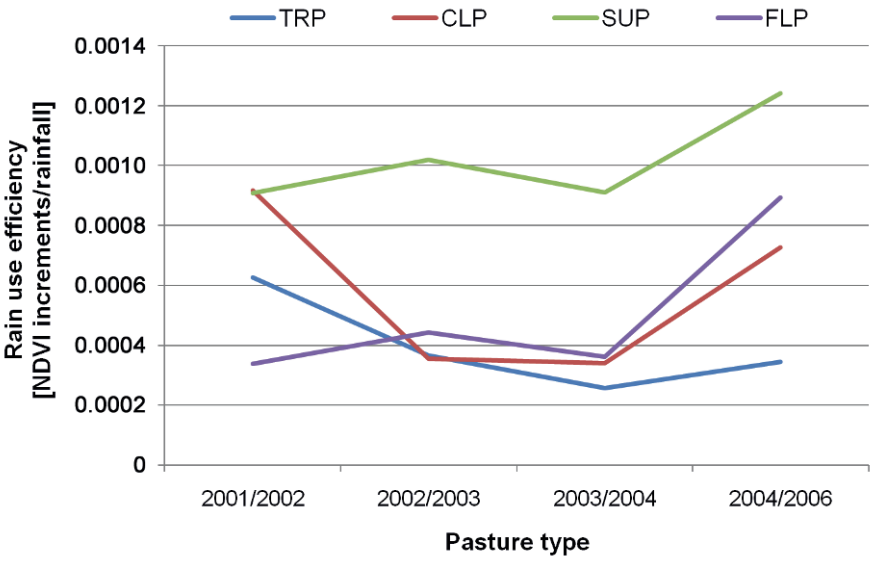

Fig. II-5.3.10: The variability of RUE (rain use efficiency) for the pasture types of the Ait Toumert pastoralists. The primary production is measured as NDVI increments around four IMPETUS climate stations Trab Labied, Taoujgalt, Imeskar, and Tichki representing the pasture types FLP (distant lowland pastures), CLP (close lowland pastures), TRP (transition pastures) and SUP (summer pastures), respectively. In all four cases, the mean NDVI increments were calculated for approximately 50 pixels around the stations in an attempt to capture a homogeneous area. For a map of pasture types, see fig. II-5.4.3.

The local ecological knowledge on fodder resources

The importance of the ecological buffers rendered by perennial forage plants is reflected by the valuation of these plants in the local ecological knowledge. A statistical match between the local valuation and the ecological performance of fodder species showed that pastoral nomads prefer woody and perennial non-woody forage species (see sect. II-5.4). Like in other heterogeneous environments (Angassa and Oba 2008), the Ait Toumert pastoralists have a complex understanding of the quality and availability of natural fodder resources. Perennial forage plants have a higher value in their perspective than herbaceous species. What makes perennial species more valuable in the local perception? On the Ait Toumert pastures, perennials are not necessarily more productive than annual species (Baumann, unpublished data, personal communication). However, they offer fodder resources that are more independent from climatic variability; they constitute an ecological buffer. For the Ait Toumert pastoralists, a high grazing value of a certain species or pasture is thus not only determined by a high production of forage, but also by a predictable availability of forage. This is congruent with other studies from arid rangelands (Adriansen 2005). Accordingly, we identify the reliability of plants and pastures to produce fodder as a key element for the local valuation (see Baumann et al. 2008; Kemmerling et.al. 2009, personal communication).

For extracting the key traits of an adaptive range management, the spatio-temporal patterns of pasture productivity and information on the resource accumulation on different pastures, which reflect principal mechanisms of how rainfall variability is ecologically buffered, can be matched with the spatio-temporal patterns of resource use. We hypothesize that the occurrence of fodder resources that are ecologically buffered (and have thus a high reliability) will be mirrored in mobility patterns:

(1) Pastures with a high reliability of fodder resources are used more intensively.
(2) Pastoralists in the Drâa catchment indirectly manage pasture reliability, which is reflected in their mobility decisions.

For our case study, we match data on the ANPP variability (see fig. II-5.3.10), and the relative abundance of perennial species (see fig. II-5.3.11) on different pasture types as an indirect measure for ecological buffers with socio-economic data on grazing frequency on these pastures. The perennial species comprise trees and shrubs, geophytes and perennial forbs and grasses. Forage is mainly accumulated by trees and shrubs, and, to a lesser extent, by perennial forbs and grasses.

Searching fodder resource reliability

Local ecological knowledge on the quality and availability of fodder on different spatial and temporal scales is a key for pastoralists' management decisions (Baumann et al. 2008, Kemmerling et al. 2009, personal communication). The decision-mak-

ing of pastoralists is linked to the local perception of the resource reliability. In our case study, the upland pastures that have a reliable proportion of perennial species (see fig. II-5.3.11) and a buffered primary production (see fig. II-5.3.10) are regularly grazed during the spring, summer and autumn (see hypothesis 1). Pastoralists are conscious about the unreliability of the distant lowland pastures where annual plant species are dominant. Their decision to move there largely depends on the resource availability in a particular year. Only in years with good rains will all households decide to move to these pastures because herdsmen know that they will find an abundance of herbaceous biomass for their livestock during these years. In other types of years, only a certain proportion of pastoral-nomadic households move there. Instead, households stay on transition pastures where more perennial species occur compared to distant lowland pastures (see fig. II-5.3.11). Thus, the mobility decisions of pastoral-nomads depend on the availability of fodder resources in general (i.e., the type of year) and specifically on the availability of fodder resources provided from perennial species. The fewer perennial species that occur on a certain pasture, the more the movement to this pasture depends on the quality of the year, except for the summer upland pastures.

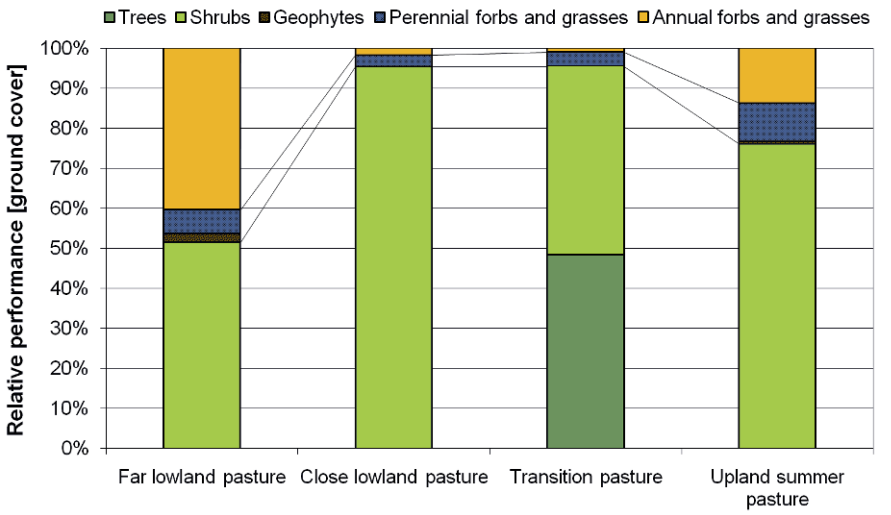

Fig. II-5.3.11: The standing crop of different life forms on the four types of local pastures arranged along a gradient of decreasing climatic aridity as well as rainfall variability. The life forms in the bars are arranged according to their lifetime, from long-lived trees to short-lived annual forbs and grasses.

Managing fodder resource reliability

Spatial patterns of range management have to be interpreted with respect to their functionality. A crisis management applied during drought times is backed by a reliability management in times with less scarce rainfall. Mobility may thus not only be a coping, but also a preventive, strategy in accumulating or maintaining local fodder storage. The mobility patterns of the local pastoralists allow an exploitation of the diversity of vegetation types along a steep altitudinal gradient, securing a continuous access to temporally highly variable resources. In intensively used temperate and subtropical grasslands, forage accumulation is actively promoted through a practice of allowing forage biomass to accumulate on a pasture until it is needed for grazing. This stockpiling of forage is an effective method to extend grazing beyond the growing season for a use during any period of expected deficiency (Riesterer et al. 2000). Forage accumulation has also been reported as an essential management strategy applied by land users in arid environments, for example where certain areas are reserved for drought times (Bollig 2006). The pasture types with the highest amount of accumulated forage are the transition pastures and the close lowland pastures. These are the ones that sustain livestock with fodder during the scarce time of the year, which is the winter in the Ait Toumert system (see fig. II-5.3.9), particularly in years with below-average rainfall (Kemmerling et al. 2009, personal communication; see sect. II-5.1). In contrast, the least variable primary production is found on summer pastures (see fig. II-5.3.10).

Investments into the ecological buffer of the vegetation

On the upland summer pastures, a highly reliable fodder production is reflected in a regular intensive use of this pasture type (see above). However, a reliable production of palatable biomass is not only sought after, but also maintained by means of the *agdal system* (for a description of the *agdal*, see sect. II-5.4). This system protects perennial species from grazing during the onset of the vegetation period when plant individuals are particularly sensitive to grazing and have, at the same time, a high recovery potential. A second mechanism of promoting resource reliability is through an indirect protection of transition pastures in years with abundant rainfall. Local herdsmen move to their far lowland pastures only in years where rainfall is perceived to be ‘good’, allowing a recovery of the perennial vegetation on their otherwise intensively used transition pastures (Kemmerling et al. 2009, personal communication; see sect. II-5.1).

The crucial importance of protecting pasture reliability through a resting in times when the vegetation recovery potential is high has been reported to build resilience in other drylands. Here it has been described as a ‘savings bank’ of forage in the event of drought (Colding et al. 2003) as the creation of a ‘natural insurance’ (Quaas et al. 2007; Quaas and Baumgärtner 2008) as an ‘ecological risk management’ (Müller et al. 2007a; Müller et al. 2007b) or as an ‘investment into the eco-

logical buffer' of the vegetation (Frank et al. 2006). Ecological reliability is thus both sought after and protected via local mobility patterns (Roe et al. 1998; Ilahiane 1999). Perceiving reliability and adjusting management decisions to this reliability are important mechanisms of resilience in these types of social-ecological systems. As an adaptive approach to dealing with uncertainty (Fernandez-Gimenez and Le Febre 2006), protecting pasture reliability increases the ability to cope with and regenerate from external shocks, such as droughts.

Naturally, the grazing impact of the local small stock herds reduces the perennial vegetation cover beyond the densities on sites protected from grazing. During a recovery period of seven years, a significant amount of perennial biomass was accumulated on most of the local pastures (Baumann et al. 2008). The recovery is highest on the most productive transition pastures. Here, more than 2,500 kg of dry matter were accumulated per hectare. The protective perennial vegetation layer became three times as dense in this time. However, the degradation of the perennial vegetation can be much worse, as observed on pastures close to permanent settlements (Baumann, unpublished data).

In summary, the Ait Toumert pastoralists invest in the ecological buffer of their pastures by delaying the grazing of summer pastures (institutionalized in the *agdal* system), and allowing the regeneration of the intensively used transition pastures in years with abundant rainfall when local herdsmen move to lowland pastures.

Functional connections among drought, flood, and erosion

Adaptive management of the perennial vegetation has important implications for the sustainability of local range management. It creates a functional connection between the effects of different extreme weather events. Because perennials effectively protect the soil from erosion (Nyangito et al. 2009), maintaining a certain density of perennial plants is an important anti-erosive measure (see subsect. II-5.3.2). Besides pasture management strategies that promote fodder resource reliability (see above), herd management during and after a drought may also play a crucial role in this context. In arid rangelands, droughts lead to frequent crashes of livestock populations (Vetter 2005; Gillson and Hoffman 2007). Due to a lagging response of livestock populations to fodder availability during and after a drought, vegetation has a certain time window to recover. To avoid a degradation of the natural resource base, it is crucial to allow pasture recovery in the years following a drought. If stocking rates are not significantly reduced shortly after drought times, the potential for accelerated erosion following the drought increases (Morton and Barton 2002). Thus, the risk of floods and erosion in the Drâa catchment is much higher if the pastoral range management is not adapted to the spatio-temporal patterns of the natural resource vulnerability.

Besides these potential effects of drought on the future impacts of severe rainfall, there exists also a connection between severe rainfall and the future effects of meteorological drought. The consequences of accelerated erosion are a reduction

of the soil depth, a decline in the soil structure and a decrease in the infiltration rate and water storage capacity. Less water stored on a site leads to a higher frequency of agronomic drought because primary production declines.

II-5.3.4 Agricultural strategies to cope with unpredictable water resources

In the rural areas of the Drâa catchment, agriculture is, besides livestock breeding, the most prominent management strategy to cope with unpredictable water resources. The variability of the climate and the environment as well as the social and political composition of the local communities is reflected in various cropping strategies adopted by the local population (see subsect. II-5.1.2).

People also manage temporal water scarcity in a direct and often institutionalized way. Here, the irrigation of fields in river oases is the basic strategy. Even in the mountainous Atlas region, which is less affected by water scarcity than the southern parts of the Drâa catchment, the agricultural productivity relies on irrigation. To establish a reliable supply of irrigation water, people not only rely on the exploitation of natural aquifers, but also establish artificial storage systems such as small dams. Nevertheless, regional or temporal water scarcities still exist. Because of the lack of arable land and the permanent cultivation of soils, land use and irrigation must be well regulated and controlled. Gaining access to sufficient water for irrigation and fertile and safe soils are the basis for the management decisions of individual families. Elaborated water management and distribution systems are a reaction to the present scarcity. In the Drâa region, two systems of water ownership and distribution exist:

1. The mulk system, where water rights are separated from rights over land. Water and land can be sold, rented or surrendered independently. Families or individuals own parts of the irrigation canals and the right to use irrigation water during fixed periods of time (nouba). Fields in different areas owned by the holder of the current water right are watered in succession. During this time-slot the farmer is entitled to irrigate his fields, regardless of the position of his field. The mulk system is used to manage scarce and contested resources.

2. The allam system, where water is attached (or in Arabic “married”) to the land. Land is always sold, rented or surrendered along with the rights to the water. Water is distributed by a rotation among branches. Arrangements between up- and downstream riparian owners are necessary to guaranty a successful distribution. This system is often applied were water availability is sufficient and therefore less contested.

Thus, local land users distinguish between the cases of a reliable supply of water resources and cases where the water supply is scarce and less reliable. They have developed two contrasting institutions that allow them to minimize conflicts over scarce water resources.

II-5.3.5 Conclusions

How to mitigate extreme events in the Drâa catchment?

The land management in the Drâa catchment mitigates drought effects on all levels of resource scarcity. Drought mitigation is – in the case of pastoralism – functionally achieved by a preventive natural resource management, particularly in times of abundant rainfall, by coping strategies during and after droughts, and through access to alternative income sources (Breuer 2007; Kemmerling et al. 2009, personal communication; see also subsect. II-5.1.4). Such an adaptive land management ensures the resilience of the whole social-ecological system in this highly unpredictable and vulnerable environment.

Although the pastoral strategies of natural resource management mainly aim at mitigating drought effects, they may, at the same time, somewhat mitigate the negative effects of high rainfall intensity, particularly erosion processes. Wind erosion, although an important process in semi-arid and arid regions, has not been dealt with here because of the great uncertainties in wind speed estimations from climate models.

We recommend that for reducing water erosion in the High Atlas region, adaptive range management strategies and more direct measures, such as small stone walls and stone terraces, should be combined. A protection of the vegetation might even outweigh the negative effects of Climate Change on water erosion (see subsect. II-5.3.2). Furthermore, official drought mitigation measures should take into account the critical time after a drought when pastures and soils are particularly vulnerable to degradation. For example, it seems more feasible to support local herd owners by subsidizing the sale of livestock or to provide supplementary fodder after a drought than to provide fodder during drought times (Drees et al. 2009). Other strategies of drought mitigation could focus on market development and opportunities for livelihood diversification (Desta and Coppock 2004; see also chapter II-5.1 for implications on livelihood security). Future investigations on land use should explicitly consider the impact of a changing climate on the soil water availability and pasture productivity and on the interactions of the rangeland vegetation with management strategies.

References

Adriansen HK (2005) Pastoral mobility: A review. Nom Peoples 9:207-214
Agnew CT, Anderson EW (1992) Water resources in the arid realm. Routledge, London
Agnew CT, Warren A (1996) A framework for tackling drought and land degradation. J Arid Environ 33:309-320
Angassa A, Oba G (2008) Herder perceptions on impacts of range enclosures, crop farming, fire ban and bush encroachment on the rangelands of Borana, Southern Ethiopia. Hum Ecol 36:201-215
Baumann G, Kemmerling B, Linstädter A (2008) Indigenous knowledge - sustainable decisions. Comparing local and scientific use of plants as indicators. In: Organizing Committee of 2008 IGC/IRC Conference (ed) Multifunctional Grasslands in a Changing World Volume II, p. 864. Guangdong People's Publishing House, Guangzhou
Behnke RH, Abel N (1996) Revisited: The overstocking controversy in semi-arid Africa. World Anim Rev 87:4-27
Bollig M (2006) Risk management in a hazardous environment - a comparative study of two pastoral societies. Springer, New York
Born K, Fink AH, Paeth H (2008) Dry and wet periods in the Northwestern Maghreb for present day and future climate conditions. Meteorol Z 17:533-551
Breuer I (2007) Livelihood security and mobility in the High Atlas Mountains. In: Gertel J, Breuer I (eds) Pastoral Morocco: Globalizing scapes of mobility and insecurity. Reichert, Wiesbaden
Carrión JS, Fernández S, Jiménez-Moreno G, Fauquette S, González-Sampériz P, Finlayson C (2009) The historical origins of aridity and vegetation degradation in southeastern Spain. J Arid Environ. doi:10.1016/j.jaridenv.2008.11.014
Colding J, Elmqvist T, Olsson P (2003) Living with disturbances: building resilience in social-ecological systems. In: Berkes F, Colding J, Folke C (eds) Navigating social-ecological systems: Building resilience for complexity and change. Cambridge University Press, Cambridge
Dahlberg AC (2000) Interpretations of environmental change and diversity: A critical approach to indications of degradation – the case of Kalakamate, Northeast Botswana. Ecol Appl 11:549-562
Desta S, Coppock DL (2004) Pastoralism under pressure: Tracking system change in Southern Ethiopia. Hum Ecol 32:465-486
Dougill AJ, Thomas DSG, Heathwaite AL (1999) Environmental change in the Kalahari: Integrated land degradation studies for non-equilibrium dryland environments. Ann Assoc Am Geogr 89:420-442
Drees R, Baumann G, Kemmerling B et al (2009) Lessons learned from transhumant pastoralism: The role of key resources in a heterogeneous environment. Transformation, Innovation and Adaptation for Sustainability – Integrating Natural and Social Sciences. Conference Proceedings, Lubljana.
www.esee2009.si/.../Drees%20-%20Lessons%20learned%20from%20transhumant.pdf.
Accessed 21 September 2009
Fernandez-Gimenez ME, Le Febre S (2006) Mobility in pastoral systems: Dynamic flux or downward trend? Int J Sust Dev World Ecol 13:341-362
Eswaran H, Lal R, Reich PF (2001) Land degradation: an overview. Oxford Press, New Delhi
Gillson L, Hoffman MT (2007) Rangeland ecology in a changing world. Sci 315:53-54
Hambler C, Canney SM, Coe MT, Henderson PA, Illius AW (2007) Grazing and "degradation". Sci 316:1564-1565
Hary I, Schwartz HJ, Pielert VHC, Mosler C (1996) Land degradation in African pastoral systems and the destocking controversy. Ecol Model 86:227-233
Hein L (2006) The impacts of grazing and rainfall variability on the dynamics of a Sahelian rangeland. J Arid Environ 64:488-504
Ilahiane H (1999) The Berber Agdal institution: Indigenous Range Management in the Atlas Mountains. Ethnol 38:21-45

IPCC (2001) Climate change 2001: Synthesis Report. Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Linstädter A, Bolten A (2007) Space matters – sustainable range management in a highly variable environment. In: Bubenzer O, Bolten A, Darius F (eds) Atlas of cultural and environmental change in arid Africa. Heinrich-Barth-Institut, University of Cologne, Cologne

Linstädter A, Zielhofer C (2010) Regional fire history shows abrupt responses of Mediterranean ecosystems to centennial-scale climate change (Olea-Pistacia woodlands, NE Morocco). J Arid Environ 74:101-110

Linstädter A (2009) Arid rangelands: Understanding a complex adaptive system. In: Bollig M, Pauli J, Schnegg M, Wotzka HP (eds) African pastoralism: Past, present, future. The emergence, history and contemporary political ecology of African pastoralism. Berghahn, Oxford

Martínez-Fernández J, Esteve MA (2005) A critical view of the desertification debate in southeastern Spain. Land Degr Dev 16:529-539

McAllister RRJ, Gordon IJ, Janssen MA, Abel N. (2006) Pastoralists' responses to variation of rangeland resources in time and space. Ecol Appl 16:572-583

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. 8th Conference on Applied Climatology, January 17-22. Preprints , 179-184. Anaheim, California

Meze-Hausken E (2000) Migration caused by climate change: how vulnerable are people in dryland areas? Mitig Adapt Strat Glob Change 5:379-406

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: Desertification synthesis. World Resources Institute, Washington, DC

Milton SJ, Dean WRJ (2000) Disturbance, drought and dynamics of desert dune grassland, South Africa. Plant Ecol 150:37-51

Morton J, Barton D (2002) Destocking as a drought-mitigation strategy: Clarifying rationales and answering critiques. Disasters 26:213-228

Müller B, Frank K, Wissel C (2007a) Relevance of rest periods in non-equilibrium rangeland systems – a modelling analysis. Agric Syst 92:295-317

Müller B, Linstädter A, Frank K, Bollig M, Wissel C (2007b) Learning from local knowledge: Modeling the pastoral-nomadic range management of the Himba, Namibia. Ecol Appl 17:1857-1875

Nyangito MM, Musimba NKR, Nyariki DN (2009) Hydrologic properties of grazed perennial swards in semiarid southeastern Kenya. Afr J Env Sci Technol 3:26-33

Olsson L, Eklundh L, Ardo J (2005) A recent greening of the Sahel - trends, patterns and potential causes. J Arid Environ 63:556-566

Owen-Smith N (2008) The refuge concept extends to plants as well: Storage, buffers and regrowth in variable environments. Oikos 117:481-483

Paeth H, Born K, Girmes R, Podzun R, Jacob D (2009) Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes. J Clim 2:114-132

Paruelo JM, Pütz S, Weber G et al (2008) Long-term dynamics of a semiarid grass steppe under stochastic climate and different grazing regimes: A simulation analysis. J Arid Environ 72:2211-2231

Prince SD, Brown de Colstoun E, Kravitz LL (1998) Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. Glob Chang Biol 4:359-374

Quaas MF, Baumgärtner S (2008) Natural vs. financial insurance in the management of public-good ecosystems. Ecol Econ 65:397-406

Quaas MF, Baumgärtner S, Becker C et al (2007) Uncertainty and sustainability in the management of rangelands. Ecol Econ 62:251-266

Retzer V (2006) Impacts of grazing and rainfall variability on the dynamics of a Sahelian rangeland revisited (Hein, 2006) – new insights from old data. J Arid Environ 67:157-164

Rockström J (2003) Resilience building and water demand management for drought mitigation. Phys Chem Earth 28:869-877

Roe E, Huntsinger L, Labnow K (1998) High reliability pastoralism. J Arid Environ 39:39-55
Samuels MI, Allsopp N, Knight RS (2007) Patterns of resource use by livestock during and after drought on the commons of Namaqualand, South Africa. J Arid Environ 70:728-739
Thurow TL, Taylor CM Jr (1999) Viewpoint: The role of drought in range management. J Range Manag 52:413-419
Vetter S (2005) Rangelands at equilibrium and non-equilibrium: recent developments in the debate. J Arid Environ 62:321-341
Wiegand T, Snyman HA, Kellner K, Paruelo JM (2004) Do grasslands have a memory: Modeling phytomass production of a semiarid South African grassland. Ecosyst 7:243-258
Zimmermann J, Higgins SI, Grimm V, Hoffmann J, Linstädter A (2010) Grass mortality in semi-arid savanna: the role of fire, competition and self-shading. Perspect Plant Ecol Evol Syst. 12:1-8, doi:10.1016/j.ppees.2009.09.003

II-5.4 Migration and resource management in the Drâa Valley, Southern Morocco

M. Rössler, H. Kirscht, C. Rademacher, S. Platt, B. Kemmerling, and A. Linstädter

Abstract

This section highlights some key elements of local social structures and societal processes that influence decision-making to secure peoples' livelihoods. Besides strategies related to natural resource management in the High Atlas region of Southern Morocco, particular stress is laid upon processes of socio-economic and demographic change in the Drâa catchment. These processes are directly influenced by the critical availability of water on a regional as well as a local scale. In this context, the process of urbanization, patterns of migration as well as ethnic affiliations, social status of individuals or groups and their effects on economic strategies are analyzed. Labor migration to the urban agglomerations in the north of the country, and also to regional urban centers, is continuously growing, resulting in both relatively low population growth in rural areas and in increasing urbanization. Remittances from migrants, as the most important source of income for the population in the marginalized rural regions, are partly used to subsidize farming or pastoral activities and are therefore crucial for the continuity of the agricultural system.

Keywords: Migration, urbanization, resource management, pastoralism, agriculture

II-5.4.1 International and national migration

In Southern Morocco, in addition to the pressure on resources due to demographic development, recurring periods of aridity over the past few decades have damaged the agriculturally-based economy. In the provinces of Ouarzazate and Zagora, natural resources are unequally distributed. In the High Atlas Mountains and the Basin of Ouarzazate, water is not as scarce as it is in the Middle Drâa valley, where water flow is controlled by the Mansour Eddahbi Dam near Ouarzazate. Nevertheless, scarcity of rain has consequences for the whole area, causing labor migration to become common among people living in communities in the High Atlas and the Ouarzazate Basin or the Middle Drâa valley. In addition to the increasingly scarce amounts of available irrigation water, the quantity and quality

of domestic water have also decreased. Anthropological investigations in the Drâa valley show that the water table in many wells is declining, not only in wells used for irrigation, but also in domestic wells located in the proximity of settlements that are used to fetch the water needed for drinking, cooking, washing and to water animals. Apart from the direct negative impacts of the water crisis, which are evident with respect to nutrition, hygiene, reproductive health, and overall quality of life, indirect economic consequences such as increasing labor migration have severe impacts on the development of the region. Migration in particular has become a key strategy for sustaining local livelihoods (see subsect. I-8.1.2). Morocco is one of the foremost sources of migrants among countries worldwide, and it also has a large number of national migrants. The main reasons for national migration are existing economic disparities within the country, with a prosperity gap between north and south. While the Atlantic coast in the north is the economic heart of the country, the south and especially the southern oases such as the Drâa valley are economically and infrastructurally marginalized. This dichotomy began during the colonial period, when Morocco was divided into a northern 'Useful Morocco' (*Le Maroc utile*) and a Southern 'Necessary' or 'Useless' Morocco (*Maroc inutile*) by the French General Lyautey (cf. Pennell 2000; Müller-Hohenstein and Popp 1990).

Although most migration studies to date have focused on international migration, national migration must not be neglected. In the region under investigation, the number of migrants moving to national destinations exceeds that of international migrants. That little attention has been paid to national migration in recent migration studies might be explained by the negative image of national migration, called '*exode rural*' in Morocco. This neglect by scholars and politicians is based on the low economic benefits of national in comparison to international migration, their theoretical focus on transnationalism, and the lack of data available to quantify national migration. Even though national and regional migration affects a large number of people, comparative quantitative data about national migrants are scarce because national migrants are not reported in published versions of national census data. This disadvantage can only be overcome through detailed local case studies that reveal various aspects of migration on a local scale. In our case study, national and international migration flows are considered simultaneously because national migration is often the first step towards international migration. Moreover, according to Skeldon, there are no substantial or logical differences between the two forms of migration (Skeldon 1997).

The application of qualitative methods allows a better understanding of the social implications of labor migration and provides a differentiated view of migrants' motivations. While in many analyses the decision to migrate is understood to be purely economically driven, it will be shown that reasons for individual migration decisions include social motivations as well. Hence familial situations, social positions in villages, questions of individual property, or personal desires of various kinds are equally as strong of reasons for migration as unemployment, demographic pressure, or droughts (Rademacher 2010).

Local informants agree that in the beginning, migration was mostly triggered by the poor economic situation. But as the number of migrants has increased, the motivations to migrate have become more diversified. Migration generates positive feedback not only through financial remittances but also through the flow of information and news, which Levitt calls 'social remittances' (Levitt 1998). The more information about living and working conditions in cities is available and the more contact points are known, the greater the willingness to migrate. Migration networks, including relatives or friends living in urban centers as well as family members who take care of property back home, obviously facilitate migration (Massey et al. 1993).

For young males especially, migration offers a unique opportunity to prove manhood and take responsibility for their (extended) families. But this commitment to the family can easily develop into an unwanted obligation when expectations of regular money transfers or presents exceed the migrant's financial means. The adherence to the traditional Arab concept of the family as a socio-economic unit, within which each member has the obligation to ensure the whole family's livelihood, makes this obligation even more demanding; individual success or failure turns into the success or failure of the whole family, with drastic consequences for social status (Barakat 1985; Rademacher 2010).

Migration on a local scale

Ouled Yaoub, a village of 1,000 inhabitants situated 30 km north of Zagora in the Drâa valley was chosen to be a pilot community for this migration study. Here the causes and effects of labor migration upon the socio-economic setting were investigated, particularly with reference to the different ethnic groups and motivations of the migrants. This marginal region is largely dominated by agriculture, and there is only a small industrial sector apart from tourism. Belonging to the Moroccan migration belt, the Drâa valley 'exports' predominantly male workers to other parts of the country while only a small percentage of workers migrate internationally. What began as young, unmarried men leaving the village on a seasonal basis to find work, primarily in construction jobs throughout Morocco, has now become a strategy that is employed by all age-groups. Influenced by the Arab concept of family, the primary goal of these migrant workers is to support their families remaining in the village. While seasonal labor migration of a small proportion of young male villagers was viewed with suspicion by locals during the 1960s, this practice became common as the village's socio-economic situation weakened.

Our work has clearly shown that besides the importance of family support, labor migration does not solely depend on economic factors but also on the personal decisions and motivations of individuals. Individual decision-making is influenced not only by the economic situation of the household and its land tenure, but by its social positioning within the hierarchical social system of the village.

Relative deprivation in comparison to other households may also be a motive for migration, as a family crisis caused by the death of a parent or divorce.

More personal motives include longing to further education or vocational training. Personal factors include self-determination, freedom, and gaining independence through earning one's own money. Successful young migrants are regarded as men as soon as they begin to contribute to family income regularly. Consequently, over the past few decades migration has become a type of ritual, a rite of passage for young males entering manhood. The age at which a youth migrates for the first time – whether to look for labor or for education – depends on the socio-economic situation of his family, the value his family places upon education, and on his own personal aspirations. Hence, youths from the age of 13 or 14 all the way up to married men in their 60s migrate for the purpose of ensuring the survival of their families in the village. All of these men continue as labor migrants throughout their entire working lives (Rademacher 2010).

Labor migrant destinations

In Ouled Yaoub three waves of migration between the late 1950s and 2006 can be identified. During the first wave that occurred in the late 1950s and 1960s, men left the village only seasonally to spend a couple of months working as farm hands in the northern part of the country. From the 1970s until the 1990s, national migration from Ouled Yaoub expanded because income from agriculture was no longer sufficient to support the extended families – partly because of the drought years of 1973-1977 and in the 1980s. Migration during this time was often organized in groups. In the mid-1970s about 20 men, guided by an experienced migrant, went to Casablanca to work in the construction sector. This was also the starting point for international migration when five men were recruited to work in France. Additional group migrations took place in 1981 to Casablanca, and in 1989 to Goulmim, the gate to the Western Sahara (also called the "Southern Province" in Morocco). From the 1980s onwards, increasing numbers of Ouled Yaoub migrants went to the Southern Province looking for work. This temporary preference was stimulated by the lower cost of living in the south as well as its booming construction sector. This trend, however, has changed over the last few years because good job opportunities in the current period have become rare. In 2006, 16 out of the 20 migrants went to northern cities such as Casablanca, Rabat, and Marrakech, while only one migrant found work in Smara in the Southern Province. Since the 1980s, the Gulf countries and Libya became additional destinations for international migration.

The most recent migration wave, predominantly characterized by individual migration, began in the 1990s. Stimulated by other migrants and the difficult labor market situation in the Drâa region an increasing number of young people quit school ahead of time, seeking employment abroad. Since then all age-groups and all families have begun participating in labor migration.

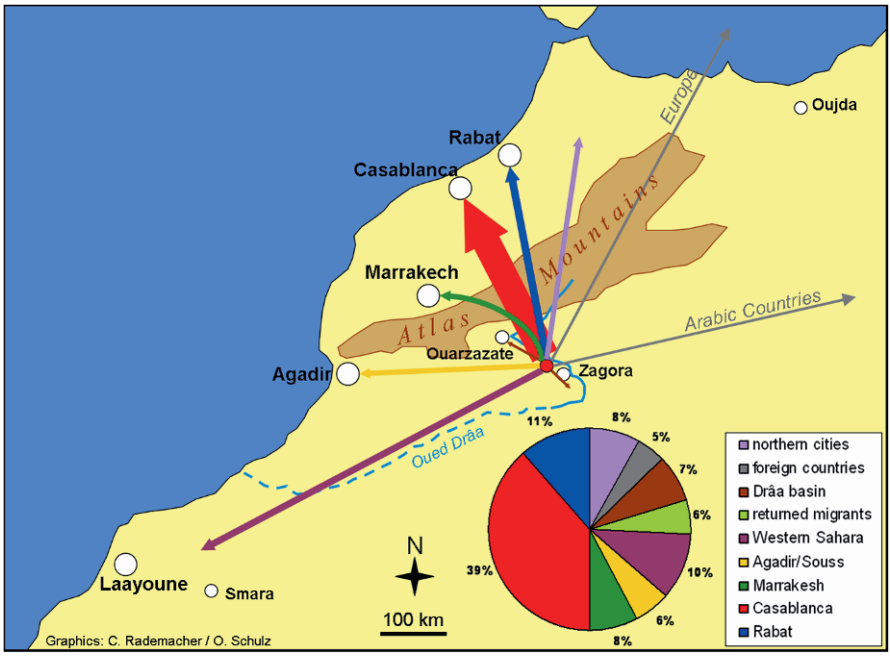

Fig. II-5.4.1: Destinations of Ouled Yaoub's labour migrants in 2004 (Source: Rademacher 2008).

Survey data from Ouled Yaoub show that in 2004 57% of the migrants found work in construction, 12% in the service sector, and the rest in various other fields. Most of these migrants were paid modestly (1,250–1,500 DH/month). Only 3% of migrants found work as civil servants, obtaining a regular and comparatively high salary. Most migrants working on construction sites are highly mobile and follow job opportunities across the country. Consequently, the information given in the map dating from March 2004 (see fig. II-5.4.1) is highly schematic and only shows the country's economic centers. That the majority of migrants receive low wages can be explained by their poor educational backgrounds. Even today, dropping out of elementary school after five or six years is common. Many migrants state that the high cost of living in the city prevents most of them from relocating their families to urban centers. In addition, socio-familial pressures oblige sons to provide financially for their aged parents, but most of them are not capable of financing two households. As a result, most families split up (Rademacher 2008).

International migration from Ouled Yaoub is low (5%), with certain European countries, Saudi Arabia, and Libya being the primary destinations. A new trend that began around the turn of the century is the (national) migration of entire families. Living together as a family, even under difficult economic conditions in the city, seems to be preferable to being separated or investing in the non-profitable agriculture of the Drâa valley. Since 2000, some 15 nuclear families have left the

village. These 15 families account for 13% of the village's households. Therefore, labor migration has increasingly turned into a definite rural-urban migration, indicating that families do not foresee an economic future in the Drâa valley.

Remittances from national and international migration

The 'new economics of labor migration' (NELM) considers migration to be a livelihood strategy used to increase and diversify household income and minimize income risks. Remittances are regarded as the main motive for migration, operating under the assumption that every migrant wishes to improve the living conditions of his household back home through sending remittances (Massey et al. 1998). In migration research however, there is no consensus in evaluating the local effects of remittances. Studies in Morocco reach different conclusions with regard to the positive or negative effects of migration and remittances on the local population.

Households in Ouled Yaoub invest remittances to cover basic needs, to renovate, construct or furnish houses, for agriculture and livestock breeding, for educational purposes, or for establishing one's own business. People agree that the living standard has improved a great deal over the past few decades due to migration.

A ranking of income sources in a sample of 20 households reveals that 65% of households regard remittances as the most important income source, while 35% declare migration as the second important source after agriculture or a local fixed salary (e.g., as a teacher). 40% of the households named revenues from agriculture – mainly from selling dates – as second in priority while 20% stated that selling sheep was a third income source. Livestock is mainly sold when households are in financial distress. Only one household is specialized in livestock breeding. Three households, all with members who have migrated internationally, own a shop in the village.

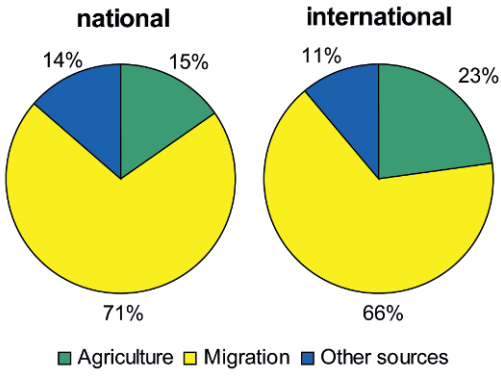

Fig. II-5.4.2: Income sources from households with access to national and international migration, Ouled Yaoub 2006 (Source: Rademacher 2010).

In figure II-5.4.2 income sources are divided between households with access to national migration and those with access to international migration. Besides income from agriculture and migrant remittances, other sources of income which include revenues from livestock sale, fixed salaries, business (shops or trade), and rental income, are listed. Households that include international migrants have a higher total income. In direct comparison, these households show a slight shift in

favor of investing in agriculture because they claim to be able to gain higher revenues (23% compared to 15% of total income from households with access to national migration only). Upon closer examination, it is striking that 20% of the households are fully dependent on remittances from migration – most of them have stopped practicing farming for good. 40% of the households have two sources of income while 30% even have three sources. Remittances from international migration are three times higher than remittances from national migration (on average 1350 DH per month). Most national migrants work in low-paid jobs and in the cities often live under precarious conditions where they cannot save any money. Even if they have savings, their incentive to invest in the rural economy is low. Instead, they prefer investing in the city and settling there permanently. We agree with Kerzazi who states that this process of rural-urban migration can only be stopped if rural regions were developed socially, economically, and technically in a fundamental way (Kerzazi 2003). What needs to be kept in mind here is that the state of the household, i.e., the number of nuclear families living within the household, the number of active family members, the number of migrants, and investments in education will probably increase household income in the future.

II-5.4.2 Resource management

Pastoral management systems – the practice of transhumance

One key area for the study of pastoral management systems is the M'Goun region in the Central High Atlas. This semi-arid environment is characterized by high climatic variability in space and time. Within this vulnerable environment, livestock management includes sedentary and mobile transhumant herding practices. Animals of the sedentary population usually stay near the villages or are kept in stables during the winter. The transhumance cycle of the mobile part of the population reaches from mountainous summer pastures in the high ranges of the Atlas to winter grazing areas in the Atlas forelands and the Jebel Saghro. Less than 3% of the area is irrigated arable land, restricted to the oases. The rest is comprised of mostly extensively-used rangelands and a few fields used for rain-fed agriculture. For all patterns of utilization, tribal affiliation is the principal way in which to gain access to common lands.

Three Berber tribes share the land rights of the M'Goun area: the Ait Zekri, the Ait Toumert and the Ait Mgoun. From west to east, they occupy neighboring strips of land. This territorial design follows 'transhumant logic', combining grazing lands with divergent environmental characteristics. In the following analysis, the strategies and mobility decisions of the mobile fraction of the Ait Toumert are analyzed. The grazing area of the Ait Toumert is collective land that includes pas-

tures solely used during spring, autumn and summer in the north, and the winter pastures in the south. The pasture areas used exclusively by the Ait Toumert are the summer and intermediate pastures in the high mountains. The mountainous summer pasture area of the Ait Toumert is called Awjgal. The intermediate pastures of Asselda and Imaun are used by the Ait Toumert in the spring and autumn. Nearby winter pastures are located at the foot of the mountains in Alatagh, Timassinine and Azweg. The basin of the Oued Dadès is divided into two pasture areas: Imlil in the north of the Oued and Saghro south of the river, which combines with the Jebel Saghro (see fig. II-5.4.3). These two grazing areas are the far winter pastures. While the summer pastures are exclusively used by the Ait Toumert, the winter pastures are shared by the neighboring fractions of the Ait Zkri (west) and Ait Mgoun (east) and other groups from the south. During winter, the three groups can move to any pasture they desire; although as a general rule, the majority stay as close as possible to their summer pastures. An important factor of collective land tenure is the traditional *agdal* institution, a common method used to protect forage plants: 'An *agdal* is a communal pasture whose opening and

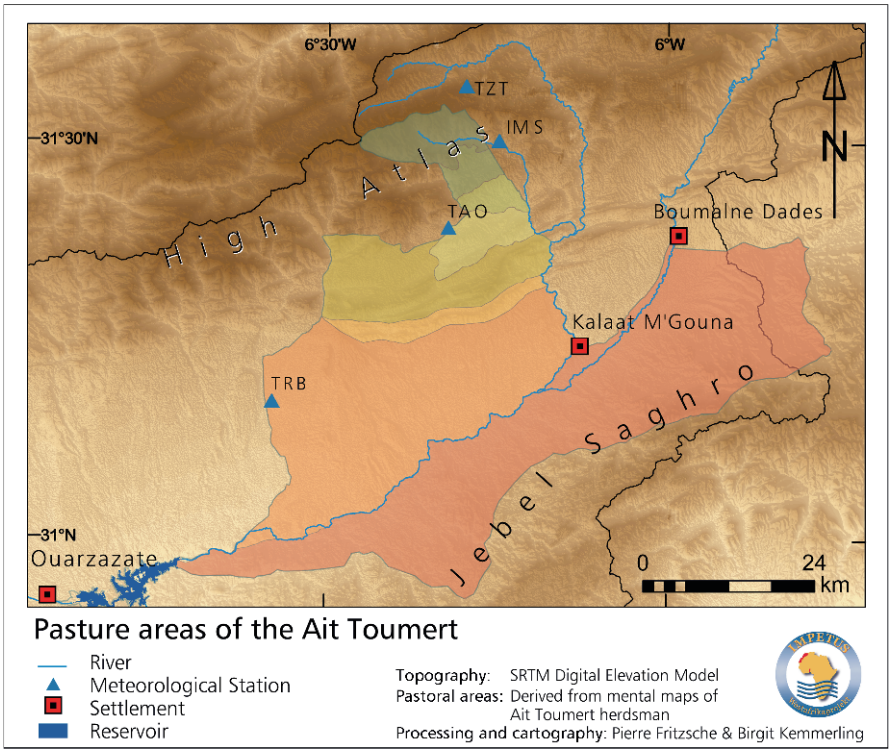

Fig. II-5.4.3: Pasture areas of the Ait Toumert (from north to south): Awjgal, Asselda, Imaun, Alatagh, Timassinine, Azweg, Imlil and Saghro (Source: Graphics by P. Fritsche and B. Kemmerling).

closing dates are fixed by the community of users. An *agdal* is a collective property used by tribal and intertribal groups: customary laws limit its boundaries and fix its closing and opening dates.' (Ilahiane 1999) Within the grazing area of the Ait Toumert, the *agdal* refers to the summer pasture of Awjgal.

The importance of local knowledge for decision-making processes

Anthropologists are interested in the emic perspective of culture and in local knowledge that enables local communities to adapt to variable environments. Within this context, local environmental knowledge is a key factor to understanding the pastoral-nomadic peculiarities of culture and pastoral strategies for sustainable range management. Pastoral-nomadic groups like the Ait Toumert must have profound environmental knowledge in order to minimize risks due to unreliable precipitation and variable access to forage plants. To understand the pastoral-nomadic exposure to natural resources, we investigated local environmental knowledge of forage plants. Information about the salience of each forage plant was collected using the free-list technique to interview 17 partners of the Ait Tou-

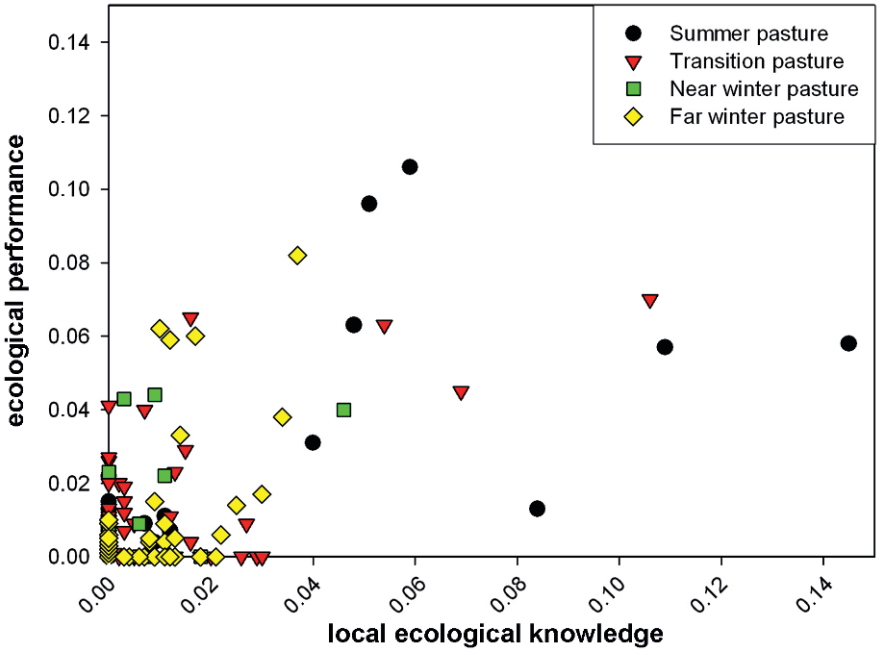

Fig. II-5.4.4: Comparison on fodder plants' weighted ranks (CSI values). The fodder plants' salience in local ecological knowledge (x-axis) is matched to ecological performance (y-axis). CSI values do not correlate significantly (r = 0.19) (Source: Kemmerling et al. 2009, personal communication).

mert. Salience was determined through the frequency of nomination and the rank of a given plant species. In the next step, local knowledge was compared with scientific ecological knowledge. The measurement of ecological performance, the relative success of a plant species in local pastures, was conducted on 96 plots of 25 m² each on summer, intermediate, near, and far winter pastures. After matching vernacular species with their scientific names, anthropological and ecological ranking lists were matched using the statistical software ANTHROPAC 4.0., equating (i) individual free-list of N interview partners with the plant species list of N vegetation plots, (ii) the rank of species in each free-list with the rank coverage of a species in each plot, and (iii) species frequency in all free-lists with species frequency in all plots (Kemmerling et al. 2009, personal communication).

No significant correlation can be observed when matching local knowledge about forage plants to ecological performance (see fig. II-5.4.4). Detailed analysis of local knowledge and ecological performance of each pasture type show that datasets correlate significantly on summer (r = 0.67) and far winter pastures (r = 0.22) (see fig. II-5.4.5). The lines of equality represent full concordance of both rankings. As regression lines demonstrate, forage plants in summer pastures are more important for herdsmen than their ecological performance suggests, whereas they are less important in the far winter pastures. Summer and intermediate pastures, where pastoral-nomads spend most of the year, are characterized by mainly perennial species, while forage plants in winter pastures are mostly annual species that depend highly on rainfall. It can be deduced that the Ait Toumert appreciate independence from climatic variability on summer pastures. Hence, local knowledge about forage plants reflects the nomads search for reliability (Kemmerling et al. 2009, personal communication).

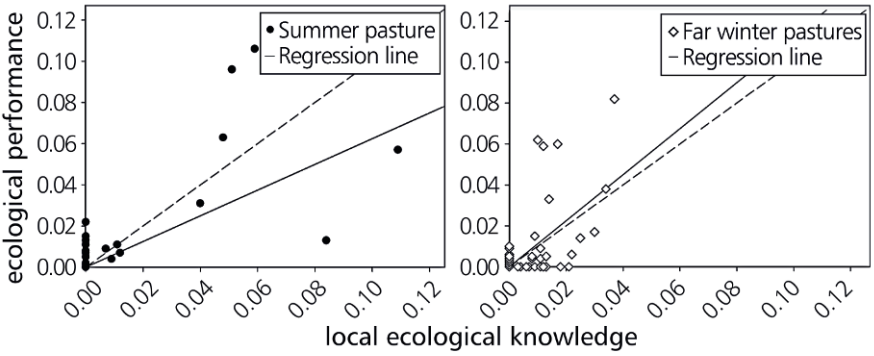

Fig. II-5.4.5: Regression analysis of fodder plants' weighted ranks (CSI values), giving local ecological knowledge (x-axis) and their corresponding ecological performance (y-axis) for species occurring on Summer and Far Winter Pastures: correlation coefficient is correspondingly r = 0.67 and r = 0.22, linear regression is f(x) = 0.62x and f(x) = 1.13x. Line of equality (f(x) = x) is dotted (Source: Kemmerling et al. 2009, personal communication).

Understanding the transhumance system of the Ait Toumert requires emphasizing the diverse range of management strategies actually used by pastoral nomads. Hence, interviews about management strategies in different types of years have been conducted with 16 herdsmen. The local perception of a year's quality mainly depends on rainfall stochastic in the different pasture areas. Range management has to be adapted to unpredictable environmental conditions. In general, the key strategy of reacting to variability in natural resources is mobility. For different types of years pastoral nomads choose various mobility patterns and specific actions from a set of alternative strategies appropriate to the year's quality.

All pastoral nomads move to the summer pasture with the opening of the *agdal*, generally from mid-May until September and pass through the intermediate ranges of Asselda, Imaun, Alatagh and Timassinine between the summer and winter months. The mobility pattern from March-April to September can be regarded as fixed. During the winter months, however, mobility patterns deviate more often from the norm due to the quality of years. In average and bad years, the majority of herdsmen move to intermediate or far winter pastures and pastures are generally changed frequently. In good and very bad years most pastoral-nomads prefer the near winter pastures. All herdsmen tend to stay the whole winter in one type of pasture. Additional alternative strategies include buying

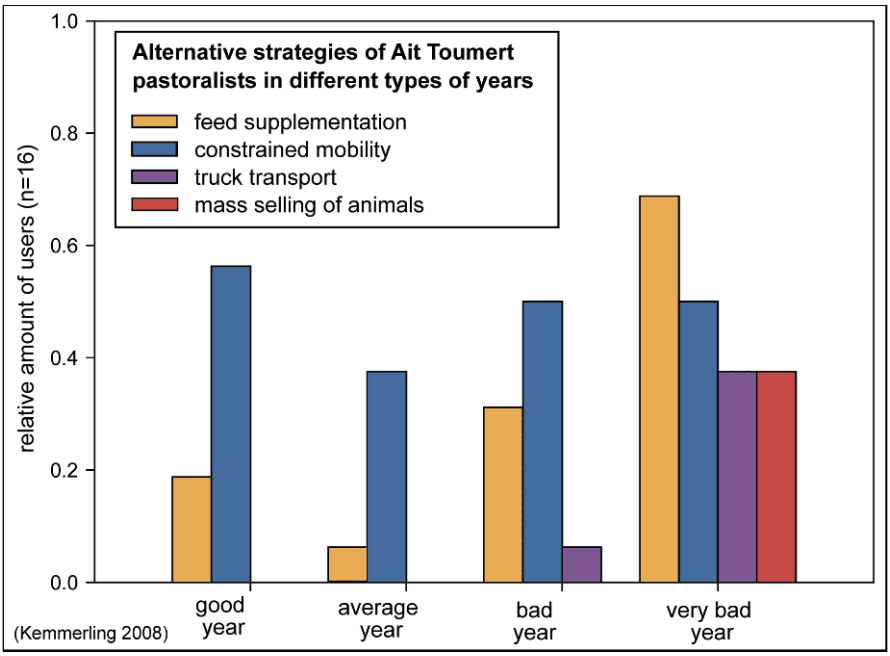

Fig. II-5.4.6: Management decisions of Ait Toumert nomads in different types of years. Amounts of decisions in a particular year depend on information of interview partners in that type of year (Source: Kemmerling 2009, personal communication).

extra fodder, which is often combined with the decision to reduce or constrain mobility during bad years. Meanwhile, buying extra fodder has become very common even in average or good years, allowing the pastoralists to avoid extensive movement and to keep the herd size high. Truck transport to remote pasture areas is another strategy exclusively followed in bad or very bad years, though only by wealthier families because a certain herd-size and capital is needed for it to be profitable. Mass-selling of animals is often used as a last resort in order to avoid a total loss in very bad years, which is practiced by a minority of the informants (see fig. II-5.4.6). Choosing diverse mobility and alternative strategies in different types of years helps pastoral nomads create reliability in their variable environment.

II-5.4.3 Conclusions

In our article we highlighted the role of labor migration and local knowledge on the management of natural resources. Nowadays in the Drâa valley in Southern Morocco, remittances from migrants are essential to sustain a decent livelihood. Due to erratic water availability caused by negative effects of the high climatic variability, droughts and management problems of the Mansour Eddahbi Dam, income from agriculture has become less and less reliable. In the mountainous areas of the northern Drâa catchments, where pastoral nomadism is still practiced as an additional income generating strategy, profound local knowledge about management options is essential to cope with environmental constraints. But even in this climatically privileged region, labor migration is important and practiced by family members in sedentary and mobile populations. Today national and international migration influence socio-economic development and the demographic dynamics of the whole working area. The income generated by migrants influences management strategies and the sustainability of pasture, land, and water use by allowing additional capital to be invested in the agricultural sector. Migrant remittances can be regarded as an additional buffer, cushioning the impact of climatic constraints on the livelihood of the local populations.

Nevertheless, this research has clearly demonstrated that labor migration does not only depend on economic factors but also on a complex bundle of motives. The personal decision to migrate depends on several factors and varies from person to person. Although economic reasons are always mentioned, social factors such as social positioning within the hierarchical social system of the village or family crisis are sometimes also dominant motives. Additionally, in areas with a long tradition of migration, such as our case of the village of Ouled Yaoub, the existence of migrant networks facilitates migration. Thus, migration becomes part of men's life cycles.

References

Barakat H (1985) The Arab family and the challenge of social transformation. In: Fernea EW: Women and the family in the Middle East: New voices of change, pp. 25-49. University of Texas Press, Austin

Ilahiane H (1999) The Berber Agdal institution: Indigenous Range Management in the Atlas Mountains. Ethnology 38(1):21-45

Kemmerling B (2008) Sustainable Range Management – Local Strategies of a Pastoral Nomadic Group in the High Atlas Mountains, Morocco. Unpublished diploma thesis, University of Cologne, Cologne

Kerzazi M (2003) Migration rurale et développement au Maroc. Univ. Mohammed V Fac. des Lettres et des Sciences Humaines, Rabat

Levitt P (1998) Social remittances: migration driven local-level forms of cultural diffusion. Int Migr Rev 32(4):926-48

Massey DS, Arango J, Hugo G, Kouaouci A, Pellegrino A, Taylor JE (1993) Theories of International Migration: A Review and Appraisal. Popul Dev Rev 19(3):431-467

Massey DS, Arango J, Hugo G, Kouaouci A, Pellegrino A, Taylor JE (1998) Worlds in Motion: Understanding International Migration at the End of the Millennium. Oxford University Press, Oxford

Müller-Hohenstein K, Popp H (1990) Marokko. Ein islamisches Entwick-lungsland mit kolonialer Vergangenheit. Klett, Stuttgart

Pennell CR (2000) Morocco since 1830 – a history. C Hurst & Co, London

Rademacher C (2008) Work Destinations of Ouled Yaoub Labour Migrants. In: Schulz O, Judex M (eds) (2008) IMPETUS Atlas Morocco: Research Results 2000-2007. 3rd edn., pp 63-64. Department of Geography, University of Bonn, Bonn

Rademacher C (2010) Gehen, damit andere bleiben können? Migration, Geschlecht und sozioökonomischer Wandel in einem südmarokkanischen Oasendorf. Doctoral thesis, University of Cologne, Cologne

Skeldon R (1997) Migration and development: A global perspective. Longman, Harlow





6 Summary and conclusions

II-6 Summary and conclusions

P. Speth, B. Diekkrüger, and A. H. Fink

IMPETUS has developed decision support tools for evaluating management options to address water-related problems for different scenarios of Global Change. The tools consist of *Spatial Decision Support Systems* (SDSSs), *Information Systems* (ISs), and *Monitoring Tools* (MTs). The so-called SMILE (Scientific Model Integration pipeLine Engine) framework has been developed, which integrates these components (see chap. II-2). The overall system is intended to be used by decision makers and stakeholders and is available to everyone interested scientifically or involved in water management (see the end of sect. II-2.3). This book was not intended as an instruction manual for the decision support tools. Rather, its purpose is to elucidate scientific results linked to these tools.

In the IMPETUS project, a combination of different regionalization methods have been used for model-based generation of regional climate scenarios, such as dynamical downscaling, statistico-dynamical, and statistical approaches (summarized in subsect. II-3.2.8). With these methods, an appropriate representation of plausible future climate pathways was determined for the two considered catchments (see sect. II-3.2.5–II-3.2.7), which is an indispensable condition for research on Global Change impacts. The variety of downscaling approaches applied under IMPETUS will remain state-of-the-art techniques for years to come.

The next paragraphs provide a summary of some results regarding the impacts of Global Change. Thereafter, the chapter ends with some concluding remarks.

Summary of some results for Benin

Under present climate conditions, physical water scarcity does not appear to be a major limiting factor for food or livelihood security in Benin. Rather, the rapid demographic growth arising from high fertility rates and immigration has caused a high pressure on natural resources such as soil, forests, water, and biodiversity. These environmental declines challenge food security and economic development. In addition to these developments, the climate in Benin is projected to undergo warming and drying trends. In parts of the sub-humid tree savannah of Central Benin, particularly in the Upper Ouémé Valley (in French: *Haute de Vallée de l'Ouémé* - HVO), farmland expanded considerably at the expense of natural forests during the IMPETUS project period of 2000–2009. The HVO had some of the highest population growth rates in Benin, in excess of 5% per year, due to immigration from the Atakora mountain area in northwest Benin. The rising population and prevailing extensive, labor-intensive cropping and animal husbandry systems were major drivers of rapid land use changes that were monitored by IMPETUS in the HVO. Migrants were strongly involved in the process of agricultur-

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al colonization. In some HVO villages, rural migrants without secure land rights already constitute the majority of the population.

Food security

The recent and future adaptive potential of Benin's cropping and animal husbandry system under the projected population and Climate Change has been discussed (see sect. II-4.1). One conclusion from agro-economic modeling was that subsidizing fertilizer use and promoting an increase in the use of organic matter and production of leguminous crops as staple food by small-scale farmers are worthy considerations to cope with demographic growth and potential drying trends. This finding was based on the assumption that labor and land scarcity are not expected to be limiting factors in Central Benin over the next two decades.

Hydrology

The IMPETUS project evaluated impacts of the projected climate and land use changes on surface runoff, soil erosion, and renewable water resources in the Ouémé catchment. One important finding is that renewable freshwater resources will decline by more than one third by the mid 21st century. Moreover, the number of months during which domestic, industrial, and agricultural water demands are not satisfied in the catchment will increase from eight months per year for the period of 2002-2014 to ten months per year for the period of 2015-2025 (see sect. II-4.2). The prolongation of the period of unmet water demands indicates the need for improvements in access to surface water and groundwater resources in this sub-humid country to avoid periods of local water stress. Additionally, river discharge is more strongly influenced by climate than by land use, which has a greater effect on surface runoff and erosion.

Land use

Agricultural land expansions are the most important change in land cover in the HVO and are occurring predominately due to the driving forces related to projections of demographic change, land use intensity changes, and related to the assumptions regarding fertilizer use. Projections of land use and land cover changes made by using the IMPETUS socio-economic scenarios highlight the consequences of road construction on the conversion of forest to agricultural lands (sect. II-4.3). These scenarios exemplify IMPETUS intervention scenarios.

Society

The coexistence of modern and customary land rights cause legal pluralism and uncertainty (see sect. II-4.4). Consequently, land conflicts emerge, purchasing land becomes problematic, and property rights are unevenly distributed. An important and poorly-recognized consequence of this land use pattern has been the inhibition of agro-forestry (e.g., cashew plantations) by traditional land owners in

large parts of Central Benin because trees are seen as property symbols in some areas of West Africa. Background information on property use and water management at the commune and village level has been given in an IS.

Health

The future spread of malaria in Benin and West Africa and the chemical, bacteriological, and microbiological contamination of drinking water in the HVO were investigated (see sect. II-4.5). In the latter context, an IS was established that contains information on present drinking water sources in the HVO. Future malaria prevalence was assessed using an improved version of the Liverpool Malaria Model (LMM) and IMPETUS climate scenarios. One important finding of this analysis was that the epidemic malaria belt in the Sahel is projected to shift southward to southern Niger, and that the malaria season in Benin might become shorter in the near future due to an overall drying trend.

Summary of some results for Southern Morocco

Coping with the impacts of Global Change is a major challenge for the vulnerable arid to sub-humid Drâa catchment and for all of Southern Morocco due to its already dry conditions and limited water availability. People rely on water not only for drinking, but also to secure their livelihood by irrigation for subsistence or cash crop farming, livestock production, small enterprises, and tourism. Other pertinent environmental issues for the area include land degradation by overgrazing, soil and water salinization from intense irrigation agriculture, and depletion of groundwater reservoirs by overuse of groundwater for irrigation. This chapter highlights examples of the ways by which Global Change might affect the future of the Drâa catchment.

Livelihood security and society

Proper water resource and land use management are important aspects of livelihood security and influence income-generating activities in the Middle Drâa basin. While crop production provides additional food and income to the basin's local population, it also involves the greatest consumption of water for the purpose of irrigation. The assessment of the impacts of Climate Change and hence changing water availability on water use for irrigation and other farm-based activities shows future consequences for income generation in the Drâa oases. Special emphasis is given to farm income, taking into account water scarcity, groundwater overuse, and irrigation-induced salinization of soil and water. To mitigate these effects, intervention scenarios were presented in subsection II-5.1.3. Examples of intervention possibilities such as the implementation of groundwater charges clearly show how altering land use policies might help the basin cope with Climate Change. However, different policy options need to be carefully eval-

uated to consider stakeholder objectives for managing the water supplies of the Middle Drâa valley. An optimal water distribution rule might lead to higher overall farm income. However, the current practice is preferable in terms of equity and poverty. A groundwater charge leads to more sustainable groundwater tables over the long run. Nonetheless, administrative costs have not been discussed here, and the implementation of a groundwater charge might not be feasible from an administrative perspective, even without considering the short-term effects to farmers' incomes.

In earlier times, the livelihoods of Drâa basin inhabitants were more heavily dependent on agricultural production than they are today. Labor migration and tourism have helped to diversify sources of income for farms and pastoral households (see sect. II-5.4). Labor migration is a common local strategy for securing work among rural populations. This migration has led to relatively low population growth in rural areas and increasing urbanization. Remittances from migrants are essential to sustaining a decent livelihood. Remittances are the most important source of income for populations in marginalized rural regions. These incomes are used partly to subsidize farming or pastoral activities and are crucial to the continuity of the agricultural system. The impact of these additional sources of income on the intensity of resource use has been considered but remains an open question. Several different incentive patterns might be at work depending on the resource endowment of the individual farm household and the source of additional income.

Hydrology

A likely decrease in surface runoff from the Upper Drâa valley into the Mansour Eddahbi reservoir is projected by scenario calculations for the future (see sect. II-5.2). This decrease in runoff is due to a decrease in rainfall. Snow coverage is also projected to decrease in the future because of rising air temperatures. Moreover, climate scenarios show a future trend towards shorter return periods for drier years, but there is no particular trend for extremely wet years. Reduced surface water availability will increase pressure on groundwater resources downstream of the Mansour Eddahbi reservoir because irrigation demand is high. Climate scenarios as well as socio-economic scenarios reveal significant impacts on water resources. Due to reduced fresh water from the reservoir, soil and groundwater salinity will increase downstream of the reservoir, eventually causing food production failures if appropriate management measures are not undertaken. While surface water availability will not be a limiting factor for upstream oases, water demands for agriculture and drinking water will not be satisfied in the Middle Drâa valley, as they have been the case recently. Thus, an increase in groundwater extraction is expected. Climate Change will lead to enhanced water scarcity and soil degradation. Changes in water use strategies will further influence the quality and availability of these resources. Thus, adapted measures can mitigate drought effects. Options for these measures are provided with the aid of intervention scenarios.

Land use

Climate scenario calculations show that soil erosion will accelerate due to reduced vegetation coverage and projected increases in extreme daily rainfall in the High Atlas Mountains. The severity of this negative effect depends on a combination of different climate and socio-economic scenarios. Key traits of pastoral land management in the High Atlas region were identified to mitigate negative effects of extreme weather events (droughts and floods) and to slow land degradation. These results showed that appropriate local land use mitigates drought effects through preventive natural resource management, particularly in times of abundant rainfall. This land use maintains or increases the capacity of rangeland vegetation to buffer against rainfall variability. Options are provided for drought mitigation that focus on market developments and reduce water erosion in the High Atlas Mountains (see sect. II-5.3).

Conclusions

IMPETUS pursued an integrated approach to management of scarce water resources in two catchments in West and Northwest Africa, respectively. Strategies for sustainable future water management at a regional level were developed while taking into account global environmental changes and socio-economic framework conditions. Research was performed for application-oriented solutions to imminent water-related and food-related problems under Global Change. The tools that have been developed to support decision-making consist of *Spatial Decision Support Systems (SDSSs)*, *Information Systems (ISs)*, and *Monitoring Tools (MTs)*. This interdisciplinary work was accomplished with the help of a unique team of scientists from the social sciences, natural sciences, agricultural science, and medicine. With regard to decision support, the IMPETUS project started by first analyzing problems, collecting data, and developing management options before initializing the development of the SDSSs/ISs/MTs for knowledge transfer (see suggested approaches in context with fig. II-2.5.1). This approach was chosen because, in many aspects, the scarcity of knowledge and data were constraints at the beginning of the project. It turned out that the methodology used by IMPETUS (see chap. II-1) was adequate and successful in developing water management tools.

The developed methodology was applied to the Ouémé catchment in Benin and the Drâa catchment in Southern Morocco. Characteristics of the catchments are summarized in chapter I-9. The methodology used here is transferable to other similar catchments in principle. However, it must be adapted to local conditions, especially with regard to the identification and respective roles of processes and mechanisms driving regional Global Change impacts on the hydrological cycle. In general, this might be feasible at a justifiable expense for the studied models, but could become quite complex for ethnological, social, and economic aspects.

Throughout different stages of the IMPETUS project, the participation of local stakeholders was implemented by two so-called “Comités de Pilotage” and by intensive capacity building of local partners. This stakeholder collaboration is a *sine qua non* for successful problem-solving and was discussed in chapter II-1 (see also the Acknowledgement at the beginning of this book).

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Acronyms

A

ABH	Agence du Bassin Hydraulique
AEJ	African Easterly Jet
AEW	African Easterly Wave
AGRA	Alliance for a Green Revolution in Africa
AMMA	African Monsoon Multidisciplinary Analyses
ANOVA	Analysis of Variance
ANPP	Aboveground Net Primary Production
AR4	Fourth Assessment Report of the IPCC
ASTER	Advanced Spaceborne Thermal Emission and Reflection
ATL	Atlantic Coast Region in Northern and Middle Morocco (Atlantic Region)
AUC	Area Under Curve
AUEA	Associations d'Usagers d'Eau Agricole
AWS	Automatic Weather Station

B

BDI	Banque de Données Intégrée
BDMET	Base de Données Météorologiques
BenEau	Water Demand Model for Benin
BenHydro	Water Availability and Consumption in the Ouémé Basin
BenIMPACT	Benin Integrated Modeling System for Policy Analysis, Climate and Technology Change
BenIVIS	Benin Inland Valley Information System
BIL	Bilan des Eaux Souterraines, Groundwater Balance Model
BMBF	German Federal Ministry of Education and Research (in German: Bundesministerium für Bildung und Forschung)
BRDF	Bidirectional Reflection Distribution Function

C

C.E.M. Drâa	Consommation d'Eau Ménagère
CATCH	Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique
CENATEL	The National Center of Remote Sensing and Forest Cover Obseravtion in Benin
CIA	Central Intelligence Agency

CLUE-S	Conversion of Land Use and its Effects at Small Regional Extent
CMB	Chloride Mass Balance
CMV	Centres de Mise en Valeur
CORPT	C=Climate, O=Organisms, R=Relief, P=Parent Material, T=Time
CROPDEM	Crop Water Demand
CropWat	Crop Water Requierements (FAO Decision Support System)
CRU	Climatic Research Unit
CWT	Circulation Weather Types

D

DEM	Digital Elevation Model
DGEau	Direction Générale de l'Eau, Benin
DGFRN	Direction Générale d Forêts et des Ressources Naturelles
DISTROAD	Distance to Road
DMN	Direction Météorologique Nationale
DRH	Direction Régionale Hydraulique
DSS	Decision Support System
DTC	Decision Tree Classifier
DWD	German Weather Service (in German: Deutscher Wetterdienst)

E

ECHAM5	European Centre Hamburg Model Version 5
ENSO	El Niño-Southern Oscillation
EOF	Empirical Orthogonal Function
EPE	Equivalent Point d'Eau
EPIC	Environmental Policy Integrated Climate
ERSDAC	Earth Remote Sensing Data Analysis Center
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EVI	Enhanced Vegetation Index

F

FAO	Food and Agriculture Organization
FOOT3DK	Flow Over Orographically Structured Terrain, 3-Dimensional, Köln Version

G

GAMS	General Algebraic Modeling System
GCM	Global Circulation Model
GCP	Ground Control Point
GDP	Gross Domestic Product
GHCN	Global Historical Climate Network
GHG	Greenhouse Gas
GIMMS	Global Inventory Monitoring and Modelling Studies
GIS	Geographical Information System
GLCF	Global Land Cover Facility
GLOWA	Global Water Cycle
GLP	Global Land Project
GNI	Gross National Income
GTS	Global Telecommunication System
GUI	Graphical User Interface

H

HCP	Haut Commissariat au Plan
HDI	Human Development Index
HRU	Hydrologic Response Unit
HVO	Haute Vallée de l'Ouémé
Hydraa	Hydrologic Model for the Drâa Catchment

I

IDL	Interactive Data Language
IGBP	International Geosphere-Biosphere Program
IHDP	International Human Dimensions Research Program
IMPETUS	An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa (in German: Integratives Management-Projekt für einen effizienten und tragfähigen Umgang mit Süßwasser in Westafrika)
iNDVI	Integrated NDVI
INSAE	Institut National de la Statistique et d'Analyse Economique
IoA	Index of Agreement
IPCC	Intergovernmental Panel on Climate Change
IRD	Institute de Recherche pour le Développement, France
IRD-CATCH	Institute pour le Développement-Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique

IRD-CATCH/AMMA	Institute pour le Développement-Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique/African Monsoon Multidisciplinary Analyses
IS	Information System
ITCZ	Inter-Tropical Convergence Zone
ITF	Inter-Tropical Front
IWEGS	Impact on Water Exploitation on Groundwater and Soil
IWRM	Integrated Water Resources Management

L

LANDSAT	Land-Use Satellite
LISUOC	Livelihood Security in the Upper Ouémé Catchment
LM	Lokal Modell
LMM	Liverpool Malaria Model
LT	Local Time
LUCC	Land Use and Land Cover Change
LUMIS	Land Use Management and Information Systems

M

MalaRis	The Impact of Climate Change on Malaria Risk in Africa (Information System)
MARA	Mapping Malaria Risk in Africa
MBR	Modified Bowen Ratio
MCP	Mixed Complementary Problem
MCS	Mesoscale Convective System
ME	Model Efficiency
MED	Mediterranean Coastal Region of Morocco and Northeast Algeria
MEDA	Mesures d'Accompagnement (EU-Mediterranean Partnership)
MFG	Meteosat First Generation
MIVAD	Modèle Intégré dans la Vallée du Drâa
MLC	Maximum-Likelihood Classifier
MMEH	Ministère des Mines, de l'Energie et de l'Hydraulique
MODIS	Moderate Resolution Imaging Spectroradiometer
MOS	Model Output Statistics
MPI-OM	Max-Planck-Institute Dynamical Ocean Model
MRT	Modis Reprojection Tool
MSG	Meteosat Second Generation
MSM	MARA Seasonality Model
MT	Monitoring Tool
MVC	Model-View-Controller

N

NAO	North Atlantic Oscillation
NCEP	National Center for Environmental Prediction, USA
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NELM	New Economics of Labor Migration
NOAA	National Oceanic and Atmospheric Administration
NOAA AVHRR	NOAA Adavanced Very High Resolution Radiometer

O

OCS	Organized Convective System
OOP	Object Oriented Programming
ORMVAO	Office Régional de Mise en Valeur Agricole de Ouarzazate

P

PBL	Planetary Boundary Layer
PEDRO	Protection du Sol et Durabilité des Ressources Agricoles dans le Bassin Versant de l'Ouémé
PESERA	Pan European Soil Erosion Risk Assessment
PMP	Positive Mathematical Programming
POPDENS	Population Density
PRO-RES	Prognosis of Snowmelt Runoff for the Reservoir Mansour Eddahbi
PROTAREA	Protected Forest Areas

R

REMO	Regional Model
RGHP	Recensement Général de la Population et de l'Habitat
RUSLE	Revised Universal Soil Loss Equation
RVF	Rift Valley Fever

S

SAF	South Atlas Fault
SahysMod	Spatial Agro-Hydro-Salinity and Groundwater Model
SAVI	Soil-Adjusted Vegetation Index
SCL	Sandy Clay Loam
SDR	Sediment Delivery Ratio
SDSS	Spatial Decision Support System
SEDRAA	Soil Erosion Risk in the DRÂA Region
SGMP	Standard Groundwater Model Package

SIQeau	Système d´Information Qualité de l´Eau
SL	Squall Line
SLISYS	Soil and Land Resources Information System
SLP	Sea Level Pressure
SMGHydraa	Statistical Model for the Generation of Climate Data for Hydrological Applications in the Drâa Region
SMILE	Scientific Model Integration pipeLine Engine
SOA	Region South of the Atlas Mountains (South of the Atlas Region)
SOM	Soil Organic Matter
SONEB	Société Nationale des Eaux du Bénin
SPI	Standardized Precipitation Index
SRES	Special Report on Emission Scenarios
SRM	Snowmelt Runoff Model
SRTM	Shuttle Radar Topography Mission
SSC	Suspended Sediment Concentration
SST	Sea Surface Temperature
SVAT	Soil-Vegetation-Atmosphere-Transfer
SWAT	Soil Water Assessment Tool

T

TDR	Time Domain Reflectometry
TEI	Tropical-Extratropical Interaction
TEJ	Tropical Easterly Jet
TERRA-MODIS	Moderate Resolution Imaging Spectroradiometer
TLU	Tropical Livestock Unit
TP	Tropical Plume

U

UEB	Utah Energy Balance Model
UHP-HRU	Universal Hydrological Program – Hydrological Response Unit
UML	Unified Modeling Language
UN	United Nations
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
UTC	Universal Time Coordinated

W

WAC	West African Craton

WEAP	Water Evaluation and Planning System
WEGE	Weather Generator
WHO	World Health Organization
WMO	World Meteorological Organization

X

XML	Extensible Markup Language
XULU	Extendable Unified Land Use Modelling Platform

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