

Advances in Natural and Technological Hazards Research

Flood Risk Management in Europe

Innovation in Policy and Practice

Selina Begum, Marcel J.F. Stive
and Jim W. Hall (Editors)

Flood Risk Management in Europe

Advances in Natural and Technological Hazards Research

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Flood Risk Management in Europe

Innovation in Policy and Practice

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To my family, friends, and the like minded colleagues who throughout this challenging editing process have sustained me with their encouragement and support, this book is lovingly dedicated.

Selina Begum

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PREFACE

In recent years flooding and the risk associated have been rising with increased frequency in many European countries. Recent floods in Europe have been a reminder of the threat that flooding poses to the wellbeing of European citizens. In 1995 250,000 people had to be evacuated in the Netherlands when extreme water levels on the Rhine threatened the dikes. Floods on the Oder in July/August 1997 submerged large agricultural and industrial areas as well as towns and villages. In 1998 and 2000 Britain suffered its worst floods in years. A recent estimate revealed that 4.5 million people in 2.3 million homes are currently at risk from flooding in UK. Flooding in central Europe in the summer of 2002 resulted in over 110 deaths and total economic damage estimates in excess of €15 billion. These alarming events have provided renewed impetus to the development of improved policies and techniques for flood risk management across Europe. There is a growing recognition that flood risk can be mitigated making space for water through sustainable management. The continents' great rivers traverse national boundaries. Basin-wide co-operation for such large river catchments can aid in adapting sustainable flood management strategies. Flood management has started focusing on practical problems, dilemmas and challenges at European scale. The European Commission has, through successive Framework Programmes, supported collaborative research that is leading to sharing of technologies across Europe and an emerging policy consensus. Flooding cannot be divorced from other policy domains in which the Commission has an important stake, such as the environmental quality of river catchments (through the Water Framework Directive) and coastal zone management.

Flood risk and vulnerability is increasing due to changes in rainfall pattern, increased frequency of extreme events, changes in land use and development in flood prone areas as a result of socio-economic demand. Human lives, property, environment and socio-economics are at increasing risk due to flooding. A combination of unexpected events and more concerted processes therefore brings us to a moment when it is meaningful to talk about Flood risk management in Europe, the title of this volume, which brings together 26 peer reviewed articles on technical, social, environmental and policy aspects of flood risk management. These articles contribute to the general themes: *flood risk management practice, flood events and impacts, flood analysis and modelling, flood forecasting and*

flood risk management policy. This volume is primarily aimed at practitioners and policy-makers who are interested in the emerging European paradigm of flood risk management and its sub-disciplines in hydrology, engineering, coastal management, economics and public policy. Some emerging technologies are presented and several future challenges are identified, so the book will be of interest to many researchers. The multi-disciplinary combination of the articles will stimulate dialogue between the various communities with a stake in the flood management process: engineers, scientists, economists, environmentalists, insurers, planners and regulators.

We hope that readers will detect the emerging themes that characterise European flood risk management resonating throughout this volume. From a technological point of view Europe is distinctive in the innovation and global reach of its several hydraulic and environmental research institutes. These are bright starts in a constellation of technological enterprises that range from market oriented technology providers to blue skies researchers. This knowledge community is a resource that is employed for evidence-based policy making. The Framework Programmes of the European Commission have increasingly stressed the importance of transferring research into practice that benefits European competitiveness and European citizens. This is not a solely technocratic endeavour. Flooding is as much a human phenomenon as it is a natural one. Flood risk management often involves making hard choices and sometimes foregoing opportunities. Developing new processes by which these choices are fair and legitimate represents a challenge to our European democratic processes. It is stimulating new methods for engaging citizens at a range of levels of decision-making.

Flood risk is a dynamic phenomenon. Society is now more vulnerable to flood damage than in the past because of our increased material wealth. Expectations for risk reduction are rising in all walks of life – occasional ingress of water into a riverside house, which might in the past have been acceptable, is now regarded as intolerable. Modification of rivers and coasts, by engineering or for environmental purposes, has changed flood frequencies, as have land use changes in catchments and impacts of climate change. The various impacts of climate change on flooding can be predicted with differing degrees of certainty. Accelerated sea level rise will be a fact of life for the 21st century at least. The evidence for changing rainfall patterns and storminess is less conclusive due to the complex hydro-meteorological phenomena. Notwithstanding these uncertainties, climate science is alerting us to the multiple sources of variability, some of which operate over very long timescales. Stationarity is looking less tenable as a default assumption.

Flood risk management is the key to the development of a long-term solution technology. Risk based forecasting and dissemination tools would be vital part in flood risk management in areas with extensive development on the natural flood plain. Flood simulation and risk assessments are indispensable strategic planning tools for effective reduction of flood risk and damage. A palpable shift in the treatment of flood risk is the new emphasis on representation of uncertainty and explicit accounting for uncertainty in decision-making. The theoretical foundations for this development were laid decades ago in the theories of stochastic

processes, structural reliability and decision-making under uncertainty, though important theoretical developments continue and disputes persist. Acceptance of the principles and methods of risk-based decision-making in practice is a more recent phenomenon, but these principles are now enshrined in the decision-processes of many, if not all, European Union member states. This is a considerable achievement as it has involved quite deep changes in world view: it is recognised that any flood defence system has a finite probability of failure; risk is to some extent socially constructed and is a multi-dimensional phenomenon; there are fundamental limits to what we know and can know about the world, but we must nonetheless make timely decisions.

Flood risk managers are therefore faced with the challenge of controlling a dynamic system with a portfolio of measures under conditions of uncertainty in order to achieve mutable societal objectives. There are no unproblematic ways of reducing flood risk. All solutions will carry some costs be it for the taxpayer, the environment, floodplain inhabitants or businesses. Portfolio of measures will include: measures to reduce vulnerability, such as land use planning and changing building practices; measures to minimise harm during flood events by flood forecasting, warning and flood fighting; and adopting flood defence measures at catchment, regional and national scales. Mitigation of climate change, but reducing greenhouse gas emissions, will help to reduce flooding especially in the second half of the 21st century. Implementing these portfolios of measures in efficient yet equitable ways represents a tremendous challenge to flood risk managers. They will need to draw upon new earth system simulation, risk analysis and decision support technologies, some of which are only now beginning to emerge. They will need to invent new governance mechanisms for our rivers and coasts to resolve conflicts and ensure legitimacy and equity. These are lofty challenges. Integrated flood risk management and a sharing of knowledge will enhance the understanding and aid in achieving a common strategy in flood risk management. Our hope is that the contributions in this volume will represent a modest step towards some solutions and provide opportunities for interaction between practitioners, researchers and policy-makers.

Publication of this pioneering volume is a timely initiative and valuable addition in the book series *Advances in Natural and Technological Hazards Research*. This book *Flood Risk Management in Europe: Innovation in Policy and Practice* has originated from the magnificent collaboration of colleagues engaged in flood risk management throughout Europe who responded very positively to the invitation in submitting papers. A companion special double issue of the journal *Natural Hazards* entitled *Flooding in Europe: Risks and Challenges* has been published (vol. 36, 1 & 2, 2005). Many thanks are due to all the chapter authors of this book for their contribution and sincere co-operation. The editors would also like to thank all the very experienced reviewers for their contribution in raising the technical quality of the book. Each chapter was subjected to critical scientific review by at least two referees/reviewers. This volume is the fruit of these endeavours. However the reviewers made such valuable contributions that we would also like to thank them separately (follows the preface).

The editors would also like to thank many individuals and organisations for their support in promoting the publication of the book. The editors wish to express their gratitude to Dr. T. S. Murty, one of the editors of the Natural Hazards journal and former president of the International Society for the Prevention and Mitigation of Natural Hazards for his inspiring introduction on the general topic *Flooding in Europe*. The editors gratefully acknowledge the assistance, support and delightful co-operation of Drs. Petra van Steenbergen, senior publishing editor of Geosciences, Springer, Mrs. Hermine Vloemans, assistant to the senior publishing editor and colleagues in the editorial and production department. Sincere thanks are also due to Mr. Henry Gomm, publishing assistant, Springer, UK for his help and assistance.

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SECTION I

FLOOD RISK MANAGEMENT PRACTICE

CHAPTER 1

DECISION-MAKING FOR FLOOD-THREATENED PROPERTIES

I. KELMAN

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Abstract: When a flood threatens an existing property such as a dwelling or business, the owner must decide what action to take to minimise the dangers, damage, and inconvenience. Extensive material is available related to options for managing the flood vulnerability of individual properties before, during, and after floods. These sources offer comprehensive information on the possibilities which exist but rarely develop tools for determining which option might be the most appropriate in given circumstances

This chapter discusses the need for, and provides some simple tools for, understanding decision-making for flood-threatened properties. The focus is on individual properties which might be threatened by floodwater, imminently (existing properties) or in the future (existing or planned properties). The decisions addressed are:

- Emphasising dry or wet flood resistance: to seal or not to seal an individual property?
- Reducing recovery duration: should property components be removed from the property before the flood, replaced after the flood, or dried and cleaned after the flood?
- Implementing resilient reinstatement: resilient reinstatement should be a social, not property-orientated, solution.

Then, the implications for the wider community context are elaborated

The U.K. is used as the main case study. The discussion helps to consolidate available information in order to produce useful analytical approaches which any property owner could use. The key is to make each property owner their own expert rather than forcing them to rely on experts

Keywords: resilient reinstatement, sealing, flood damage, property vulnerability, decision making, floods, U.K., built environment

1. INTRODUCTION

When a flood threatens an existing property such as a dwelling or business, the owner must decide what actions to take to minimise the dangers, damage, and inconvenience. Extensive material is available related to options for managing the

flood vulnerability of individual properties before, during, and after floods. For example, in the U.K., the recent literature includes Bramley and Bowker (2002), BRE (1997), BRESI (1996), CIRIA (2004), Crichton (2001), Crichton (2003b), DTLR (2002), EA (2004), EA/CIRIA (2001a), EA/CIRIA (2001b), Kelman (2001), Kelman and Spence (2003a), Lewis (2004), NEH (2004), and SEPA (2004). Advice commonly relates to:

- Dry flood proofing a property, i.e. trying to keep floodwater out such as by sealing openings or raising the property (which, realistically, is increasing flood resistance rather than “flood proofing”).
- Wet flood proofing a property, i.e. permitting floodwater to enter but minimising damage such as by using flood-resistant materials and finishes (which, again, is increasing flood resistance rather than “flood proofing”).
- Relocating a property or community.
- Designing a community to prevent floods impacting properties, such as drainage patterns which discourage surface water ponding near properties and street layout which prevents large water velocities impacting properties.
- Otherwise altering the flood hazard parameters which affect properties and communities through:
 - structural (hard) flood defences such as dams, levees, and walls; and
 - non-structural (soft) flood defences such as wetlands and parks.
- Efficient and effective return of the property to a pre-flood, or better, state after the flood event.

Much of this material emphasises that buildings must do more than resist or avoid floods. Their adequate recovery and subsequent prolonged resilience are essential for their longevity and, most importantly, the recovery, resilience, and longevity of the occupants and the community.

These sources offer comprehensive information on the options which exist but they often do not develop tools for determining which option might be the most appropriate in given circumstances. As with many decision-making dilemmas, defining the most appropriate option depends on the criteria being considered and the most important criteria according to the judge. This chapter illustrates potential analytical strategies. Each user would then need to apply their own perspective to resolve their own decision-making dilemma.

Because this chapter’s approach is scientific, it might be unsuitable for many property owners. Instead, the core audience is likely to be policy makers and technical and scientific support staff who prepare, communicate, and disseminate the information to property owners. Irrespective, it would be hoped that the tools and methods presented here might be of sufficient interest and importance to motivate property owners into acquiring the relatively low level of scientific understanding necessary for them to appreciate the background, wider context, and relevance of the material presented. As implied already, the most appropriate option in a decision-making dilemma often depends on the decision-maker’s perspective. Thus, a decision-maker should ensure that they fully understand the decision’s context, the option, and their own perspective.

This chapter discusses individual properties which might be threatened by floodwater, imminently (existing properties) or in the future (existing or planned properties). Thus, it is assumed that many of the above solutions have not been implemented, a common situation. Hence, the occupier must make a decision regarding potential flooding of their property.

The decisions addressed for individual properties are, in order:

- Emphasising dry or wet flood resistance: to seal or not to seal an individual property?
- Reducing recovery duration: should property components be removed from the property before the flood, replaced after the flood, or dried and cleaned after the flood?
- Implementing resilient reinstatement: resilient reinstatement should be a social, not property-orientated, solution.

For technical background on identifying these decisions, see Kelman and Spence (2003a).

Despite the focus on individual properties, no discussion would be complete without examining implications for the wider community, hence the community context is elaborated at the end. The main community issues investigated are:

- The appropriateness of structural flood defences.
- Property layout within a community.
- Community layout, such as topographical and land-use changes.

The U.K. is used as the main case study in this chapter in order to take advantage of the aforementioned work. This chapter helps to consolidate that information in order to produce useful analytical approaches which any property owner could use.

2. TO SEAL OR NOT TO SEAL?

During a flood, a property owner's inclination is often to seal the property in order to prevent floodwater infiltration. The goal of sealing is questionable because buildings are naturally leaky and it is difficult to be absolutely certain of keeping all water out of all possible entry points. Furthermore, if the property were sealed without using a rigid, self-supporting barrier, then water pressure would be transferred directly to the dwelling with the possible consequence of structural damage.

Floodwater pressures have many components, termed "flood actions" by Kelman and Spence (2004) who categorised and analysed them. Flood actions include debris impact, corrosion due to chemical contaminants, changing hydrostatic pressures due to waves, pressures from breaking waves, lift due to buoyancy, and scour undermining foundations. Kelman and Spence (2004) explain that three flood actions are relevant for first-order analyses.

The first flood action is water contact damage; that is, damage caused by material getting wet, not by any physical force applied by the water. Water contact damage is traditionally explored through functions correlating property damage with final flood depth and by assuming that the water rises slowly, hence no physical force

is applied by the water. For the U.K., see, for example, [Experian \(2000\)](#), [N'Jai et al. \(1990\)](#), and [Penning-Rowell et al. \(1992\)](#).

The second flood action is floodwater rising outside a sealed property without rising at the same rate on the inside of the property thereby yielding a depth differential between the inside and outside of the property. The third flood action is flowing floodwater imparting a velocity pressure onto the property's walls. Sealed properties would experience the flood actions of external water contact from flood depth along with the lateral pressures from floodwater depth differential and velocity (Figure 1).

To understand the structural stability of sealed properties subjected to these flood actions, [Kelman and Spence \(2003b\)](#) analysed the behaviour of walls in modern dwellings in England under the load from floodwater depth differential and velocity. They examined typical cavity walls—a blockwork inner leaf and a brickwork outer leaf—for dwellings between 1 and 4 storeys high.

Their results show that with no flood velocity, many dwelling walls would be structurally damaged, possibly to the point of collapse, at a flood depth differential of approximately 1.0 m. Almost all walls would have failed by the time the flood depth differential reaches 2.0 m, about 0.5 m below the height of an average storey. Considering flood velocities, relatively fast flow rates of 5–10 m/s would be needed to significantly contribute to wall failure. Therefore, depth differential is the most important parameter and keeping water out of a dwelling can lead to structural damage at low depth differentials of 1.0 to 1.5 m ([Kelman and Spence, \(2003b\)](#)). [EA/CIRIA \(2001b\)](#) suggests not sealing a property for flood depths greater than 0.9–1.0 m which matches these results within an appropriate safety margin.

The decision-making dilemma “To seal or not to seal?” thus arises. A property might need two options: (1) to seal if the maximum pressure differential is forecast to be below the level which would cause structural damage and (2) not to seal if the maximum pressure differential is forecast to be above the level which would cause structural damage. A solution combining these two options would be to seal

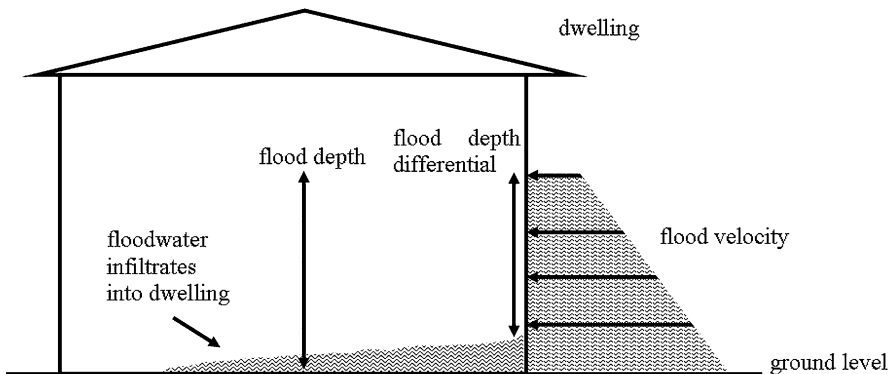


Figure 1. The three flood actions considered

the property only to the level at which structural damage would result or, more appropriately, to the 0.9-1.0 m level suggested by [EA/CIRIA \(2001b\)](#).

To understand more comprehensively the issues involved, a simplified decision-making dilemma which assumes only choices of sealing or not sealing, is in Table II. The floodwater has two possibilities: the pressure could cause structural damage or not. The property owner has two choices: to prevent infiltration by sealing or to permit infiltration by not sealing. Depending on the nature of the floodwater depth differential and velocity, sealing yields an outcome of either low-to-medium loss (some water contact damage) or high loss (structural damage). Not sealing always yields the outcome of medium loss (water contact damage) irrespective of the flood actions considered.

On occasion, the ultimate flood level or the resultant risk of structural damage might be uncertain. For example, if structural damage occurs at $1.4\text{ m} \pm 0.2\text{ m}$ and the flood level is forecast to be $1.0\text{ m} \pm 0.3\text{ m}$, the decision is not clear. If this property were sealed assuming a flood level of 1.0 m, the wake from a vehicle driving through the water or wind-induced waves could be enough to precipitate structural damage. A flood level forecast might not even be available. So how could a decision be made?

Two more criteria must be considered. First, the ease of implementing either of the two decisions. Second, the ease of changing any of the outcomes.

Regarding the ease of implementing a decision in Table II, permitting infiltration is easier than preventing infiltration. Properties are generally designed with enough leakiness for significant rates of air ventilation, from the ground to the roof ([Orme et al., 1998](#)). Completely eliminating infiltration requires surrounding a property with a continuous, impermeable barrier, such as plastic sheeting or rigid walls (e.g. see [EA/CIRIA, 2001b](#); [Crichton, 2003b](#)).

Alternatively, preventing infiltration through only the main routes such as underneath doors and through air bricks could be attempted by using sandbags, although the property's placement might preclude this possibility (Figure 2). Homemade or commercially-available flood barriers which cover openings are generally more effective than sandbags ([EA/CIRIA, 2001b](#)). These products require investment, knowledge on proper use, maintenance, and adequate warning. Whilst in operation, inconveniences occur, such as difficulty in entering or leaving the property and lack of ventilation to the wall's cavity.

Table 1. Decision-making matrix for sealing or not sealing

Flood ↓ Option →	Prevent infiltration (Seal)	Permit infiltration (Do not seal)
Pressure could not cause structural damage.	Outcome is water contact damage to external parts of the property.	Outcome is water contact damage.
Pressure could cause structural damage.	Outcome is structural damage.	Outcome is water contact damage.



Figure 2. For some riverside properties, sandbags could not protect openings, such as those in the photograph (Cambridge, England, 2001)

Permanently reducing sources of infiltration is a longer-term solution. Postal flaps could be raised or replaced by post boxes. All doors and windows could be weather-stripped which has further advantages for energy efficiency and weather-tightness. Existing properties could be retrofitted with, and new properties could be built with, concrete rather than timber floors, on the assumption that rising groundwater would not threaten to break the concrete floor. Otherwise, potential damage from a broken floor would need to be weighed against water contact damage from permitting infiltration.

These solutions, however, reduce without eliminating the flood infiltration rate. A flood lasting more than a few hours, a usual situation, could still inundate the property causing water contact damage.

Entirely eliminating infiltration without a stand-alone, rigid boundary around a property is challenging and, often, might not be feasible. Even with such a defence, undermining or overtopping of the barrier could occur along with groundwater rise or surface water ponding inside the barrier's perimeter.

In contrast, permitting infiltration is simple: do nothing. The process could be facilitated by lowering postal flaps and opening doors or other openings (Figure 3). Opening doors and windows has security disadvantages yielding the possibility that occupants could be encouraged to remain in their property leading to an increased risk to life.

Regarding the ease of changing the outcomes in Table II no easily implemented solution exists for strengthening walls or for preventing structural damage due to flood actions (Kelman and Spence, 2003b). Substantial investment and expert advice would be required for retrofitting existing properties. Building new properties to withstand expected pressures would be feasible but would require alterations to currently standard designs and, potentially, increased resource use.

In contrast, reducing damage due to water contact is relatively straightforward. Immediate actions include storing valuables on upper storeys and removing carpets from ground floors. If an appropriate plan has been made, including planning to have help if needed, and if a flood warning is received in time, most contents



Figure 3. Opening doors lets floodwater flow in or out (Malton, England, 2000)

could be removed from danger. Living in bungalows or ground floor flats makes this process more challenging raising the question why such properties are built in flood-vulnerable locations.

Longer-term solutions ([CIRIA, 2004](#); [Dixon, personal communication, 2001](#); [DTLR, 2002](#); [EA/CIRIA, 2001a](#); [EA/CIRIA, 2001b](#); [floodforum.net, 2002](#); [Kelman, 2001](#); [Lewis, 2004](#)) for ground floors include:

- Raising electric and telephone cabling so that floodwater must rise higher to reach and damage them.
- Installing drains with one way valves in ground floor rooms.
- Using water- and contaminant-resistant paint and other finishes.
- Raising the property farther above ground level, preferably during construction of new properties but feasible for retrofitting existing properties.

Flood management, however, should not be considered in isolation because proposals could have drawbacks. Some water-resistant finishes (e.g. swimming pool tanking) produce off-gassing, posing a health risk ([floodforum.net, 2002](#)). Improper installation or maintenance of drains and valves could lead to sewage backing up into the property. Raising the entire property could make life difficult for elderly or disabled occupants—many of whom must live in bungalows or ground floor flats. Then, a valid question is the reason for vulnerable individuals settling in flood-vulnerable locations. Conversely, some solutions have dual advantages. Raising electricity sockets may assist in preventing babies or toddlers from sticking metal objects into outlets.

Irrespective of the challenges involved, many solutions and options exist for reducing damage due to floodwater contact. Given the low depth differential required for structural damage, permitting water to enter a property could be simpler,

longer-term, safer, and more effective than attempting to decide when to seal and ensuring that sealing is completed properly.

Whether or not occupants would accept floodwater entering their property, and would adapt their lifestyle and properties to make this option work, is a difficult sociological question. Nonetheless, it is frequently suggested (e.g. [BRESI, 1996](#); [EA/CIRIA, 2001b](#); [floodforum.net, 2002](#); [Kelman, 2001](#); [Lewis, 2004](#)) and has been implemented for several properties in England (e.g. Dixon, personal communication, [2001](#); [DTLR, 2002](#)).

This technique is not new. [Lewis \(1979\)](#) notes that traditional dwellings in Chiswell in southern England were built assuming that water would enter non-habitable sub-floor spaces during floods: “The older cottages had stone or well-seasoned timber floors with flood ducts beneath. Occasional sea flooding was an accepted fact of life” (see also [Lewis, 1999](#)). Furthermore, [DTLR \(2002\)](#) and [EA/CIRIA \(2001b\)](#) advise limits on the height to which properties should be sealed against floodwater entry because otherwise “keeping water out of your property can do more harm than good” ([EA/CIRIA, 2001b](#)). These references indicate the viability of permitting, and perhaps encouraging, floodwater entry plus the need to make this option more socially acceptable.

In considering the consequences of making a wrong decision, again, always permitting infiltration is superior to sometimes preventing infiltration. If the choice were to permit infiltration, then the consequences are known: water contact damage, easily reduced by appropriate changes to the property. In contrast, if the choice were to prevent infiltration but then the flood level is deeper than expected, structural damage could result.

Nonetheless, despite the logic of the analysis, care must be taken and wider issues must be considered before assuming that permitting infiltration is inevitably the best option. In particular, the sociological challenges of convincing people that permitting infiltration is appropriate should not be underestimated. Imagine telling a homeowner to open their door and to let the cold, dirty, smelly floodwater wash all over their newly-renovated but non-flood-resistant lounge and kitchen. That person could be criticised for having ignored the most sustainable long-term option, but the reality is that they made their choice. Nonetheless, permitting infiltration could and should be presented as advice to the homeowner. As a feasible option, it deserves careful consideration.

In promoting the infiltration option, weaknesses in the analysis must be articulated, particularly the extensive assumptions involved. Contamination of the floodwater—for example by sewage, petrol, or salt for ocean flooding—is hardly considered. The engineering theory used by [Kelman and Spence \(2003b\)](#) for the wall failure analysis is not fully developed. One key parameter, a friction coefficient between masonry and mortar, has not been empirically examined. Engineers estimate a value and use it for the calculations, which was the procedure adopted by [Kelman and Spence \(2003b\)](#).

Health and safety implications could result by encouraging people to permit infiltration if they also choose to stay in their flooded dwellings. Boat or helicopter

ambulances would be needed in case of medical emergencies. Occupants would need food and water supplies to outlast the flooding or would need to own a boat and have been trained in appropriate boat-handling skills for extreme conditions. Other flood actions including debris and waves have not been considered in this analysis yet could cause much more structural damage than depth differential or velocity (Kelman and Spence, 2004), thereby posing a danger to anyone still in the property.

Rather than providing a definitive recommendation, the key is that this analysis and discussion have been completed and that advice and feasible options can be provided. Property owners can therefore understand the issues, the methods, and the weaknesses in the methods in order to make their own informed decisions. The importance of Table 1 and the accompanying discussion is not to recommend which choice should be made to resolve perfectly the decision-making dilemma in all circumstances, but to provide everyone with the appropriate understanding to make the choice which is best for them. Thus, it goes beyond the information normally provided for the flood management of individual properties and suggests how that information could be used to make an informed decision.

3. OTHER ANALYTICAL STRATEGIES FOR INDIVIDUAL PROPERTIES

Property vulnerability management decisions other than those related to sealing can be similarly analysed. Duration—how long a property is flooded—is often considered to be an important flood hazard parameter for determining the damage that would result (e.g. Hubert et al., c. 1996; Islam, 1997; Kato and Torii, 2002; Torterotot et al., 1992; USACE, 1994). In the U.K., Penning-Rowsell and Chatterton (1977) systemised the assessment of the benefits of flood alleviation for both urban areas and agricultural land using synthesised data for direct floodwater damage. They provided depth-damage curves for two arbitrary flood durations: “short” which is less than 12 hours and “long” which is more than 12 hours. This distinction has frequently remained in U.K. work (e.g. N’Jai et al., 1990; Penning-Rowsell et al., 1992).

Duration could also be considered as a flood vulnerability parameter. In this case, duration would refer to the time required to turn a flooded property into a pre-flood, or better, state; i.e., the time for post-flood recovery.

This post-impact duration is often many months for properly drying, cleaning, repairing, and redecorating flood-affected but non-flood-resistant U.K. properties:

- DTLR (2002) provides examples of properties which required several months to dry out following flooding and, regarding groundwater flooding, notes that “Properties can still be underwater many months after the heavy rains that caused the flooding have passed”.
- EA (2001) suggests that for flooded properties “current time to re-occupy is typically 1 year”.

- On [floodforum.net](#) ([2002](#)), the U.K. properties of Anne Bury, Colin Walsh, and “Mr. Ryder” were flooded in October 2001 and no one expected to move back in until at least six months after the event. Jemma Mclay-fortune of Ironbridge, England was flooded in September 2000 and re-occupied at the end of July 2001.
- CIRIA ([2004](#)) comments “A brick dries out at about [0.0254 m] a month so be aware that it may take several months for the brickwork to completely dry out” and “It is important to remember that if a building is seriously flooded it may be a case of several months before it becomes habitable again and it can be many weeks before it dries out”.
- EA/CIRIA ([2001a](#)) notes that “It is difficult to estimate how long a property will take to dry out... In the case of acute flooding, be prepared for the process to take months rather than weeks”.

Improper rehabilitation of a property following a flood could result in long-term damage or deleterious health effects due to mould ([CIRIA, 2004](#); [floodforum.net, 2002](#); [NEF, 2004](#)).

Some information on property flood vulnerability mitigation implies that properties should not be built with materials requiring replacement following a flood; e.g., chipboard for floors or cupboard fittings (e.g. Bramley and Bowker, [2002](#); [CIRIA, 2004](#)). If this suggestion were accepted, then the material used must be made resilient and resistant to flood damage from most flood actions. Otherwise, if materials requiring months to dry were used, then the cheapest, quickest, and easiest option could be using replaceable materials. Materials used in properties could be selected for efficient replacement just as they might be selected to be resilient and resistant to flood damage from most flood actions.

One concern would be the waste produced. A solution which advocates efficient replacement over efficient drying and cleaning would produce large amounts of potentially contaminated waste (Figure 4).

One system which uses damageable materials without requiring replacement following each flood is to make the damageable components removable. Examples



Figure 4. Flooded contents contaminated by mud await disposal (Bevendean, England, 2000)

include detachable cupboard doors and loose-fitting rugs rather than fitted carpets (Bramley and Bowker, 2002; CIRIA, 2004; DTLR, 2002). The assumption is that the occupant would have sufficient warning time and ability to move all removable components to a flood-secure place. If this place were within the affected property—an expected situation—and if the property were destroyed by flood actions, then this approach would be unhelpful because the entire property and its contents would be lost (Table 2).

Some additional notes regarding the restoration option of “dry and clean components”:

- Unanticipated contaminants could yield restoration problems.
- Generally, the quicker the process is commenced, the more effective this option becomes and the less time this option requires.
- If restoration were completed improperly, then long-term damage or major health problems could result (CIRIA, 2004; floodforum.net, 2002; NFF, 2004).
- Replacement of a property and its components always occurs at some time scale through maintenance and redevelopment, irrespective of any flooding.

Some additional notes regarding the restoration solution of “replace components”:

- The extreme case of making the entire property replaceable after every flood is unlikely to be viable due to factors such as cost and the owners’ psychological interest in maintaining their same home.
- Using cheap but easily replaced construction materials could lead to other problems including poor wind safety and inadequate thermal comfort.

In contrast to Table 1, the outcomes in Table 2 cannot be changed. Hence, the decision might be influenced most by the ease of implementing an option. In particular, prominent factors for choosing the most appropriate option would be the initial cost of each option, the cost of each outcome, and the expected likelihood of each damage scenario. Criteria other than flood damage—including aesthetics, child safety, and component utility—would be considered. Combinations are possible. For example, DTLR (2002) does not state that flood-vulnerable materials should be avoided in kitchen storage units, but does suggest that they should be raised so that replacement is not necessary following shallow floods.

Table 2. Decision-making matrix for post-flood restoration of property components

Flood damage ↓ Option →	Replace components	Remove components	Dry and clean components
Water contact	Outcome is replacement.	Outcome is removing and returning.	Outcome is drying and cleaning.
Structural damage	Outcome is replacement.	Outcome is removing and returning; possibly some replacement.	Outcome is drying and cleaning; possibly some replacement.
Property destruction	Outcome is replacement.	Outcome is replacement.	Outcome is replacement.

The cost and time for implementing an option could depend on the extent of local flooding and the choice made by nearby occupants. If all flooded occupants were to pick the same option, then these goods and services would be in high demand, potentially raising the cost and lengthening the time to complete the restoration. On the other hand, a balance amongst options, and amongst different methods of implementing each option, would place less demand on the needed goods and services. All properties could be restored more cheaply and more quickly than if only one option were selected for all properties.

In restoring flooded properties, “resilient reinstatement” is promoted (ABI, 1999; Crichton, 2001; Crichton, 2003a; floodforum.net, 2002). Resilient reinstatement involves increasing the flood resistance and resilience of a property while repairing flood damage. All suggestions in this chapter for altering a property to better manage flood vulnerability could be part of resilient reinstatement. Aspects of flood resistance and resilience could be added to U.K. Building Standards so that a requirement for resilient new developments more readily achieves resilient reinstatement for flooded existing developments (Crichton, 2001; Crichton, 2003a).

The principle of resilient reinstatement could go beyond specific construction approaches. For example, a broad definition of resilient reinstatement could imply rebuilding the property in a less flood-vulnerable location. Alternatively, with adequate financial assistance, the property owners could abandon the flooded site and purchase an existing and less flood-vulnerable property elsewhere. At the other extreme, resilient reinstatement could mean that no changes to the property are made. Instead, owners would accept that flood damage to their property would occur frequently.

By focusing on the needs of the owners and occupants, rather than the specific objective of reducing or preventing flood damage, resilient reinstatement becomes a social solution which could sometimes involve technical aspects, ranging from raising electricity sockets to raising the entire property.

Another issue regarding the choice between drying/cleaning and replacement, which would also affect choices for resilient reinstatement, relates to the behaviour of masonry units in flooding. BRESI (1996) states that:

Lightweight concrete with its relatively high moisture movement may expand on wetting and therefore shrink on drying. This may result in some cracking. Masonry materials in external walls can be prone to frost damage for about three weeks after flooding because moisture contents could be higher than under normal wetting and drying.

No indication is given regarding the seriousness of the damage. If cracking occurs to such an extent that significant remedial work is required, then Tables 1 and 2 should consider this factor. Allowing water to enter so that internal walls become wet could result in significant repair work. The equivalent of extensive structural damage could be reached by permitting infiltration and by choosing the drying/cleaning option for walls.

The focus on lightweight masonry materials for some of BRESI's (1996) comments suggests that using denser masonry units might be appropriate for

property flood vulnerability reduction. Kelman and Spence (2003b) suggest increased density of masonry units as a possible solution to increase wall strength. In this instance, using denser material assists in two ways. In contrast, Kelman and Spence (2003b) also recommend increased masonry thickness to increase wall strength yet BRE (1997) notes that increasing masonry thickness increases drying time following a flood. In this instance, choosing the optimum masonry thickness yields a tradeoff between increased wall strength and reduced wall drying time.

As with sealing, the options, complexities, and tradeoffs presented here do not provide definitive recommendations, yet provide the needed understanding for each owner to make their own choice which is best for them. In some cases, one owner's decision affects the decisions of neighbours and the wider community. An added level of complexity and feedback has emerged about each individual's optimal choice being influenced by the choices of others. Managing the flood vulnerability of individual properties cannot be done in isolation by each owner. Community collaboration is helpful for best results.

4. THE COMMUNITY CONTEXT

Decision-making for individual flood-threatened properties cannot be fully understood without considering the community context. In developing community-wide flood management strategies, considering the key flood actions of depth differential and velocity is also necessary. Otherwise, analyses such as cost-benefit analysis might be skewed creating a misguided impression of appropriate solutions.

USACE (199d) provides a good example. USACE (199d) analyses the flood damage effects of a proposed levee by calculating the estimated difference between a depth-damage curve without the levee and a depth-damage curve with the levee. USACE's (199d) analysis assumes that as soon as the 6.68 m levee is overtopped, the damage would exactly equal the damage for a slow-rise 6.68 m flood in the absence of the levee. This assumption is optimistic because:

- Without regular flooding at lower depths, the population would normally be less prepared for any flood which occurs, thus incurring more damage at higher flood levels (Etkin, 1999).
- The flood actions from a levee which overtops are expected to be different, likely with higher depth differentials and higher velocities, than a flood of similar depth in the absence of any flood defence (Kelman, 2001).

Analysis of the impact of a structural flood defence on flood damage in a community should factor in the depth differentials and velocities, particularly regarding how the structural flood defence could exacerbate the effects of these actions.

The failure mode of a structural flood defence would partly determine the impact of these flood actions. A breach or collapse of a structural flood defence would be expected to yield higher depth differentials and velocities than overtopping. The timing and values of these parameters' maxima would also vary amongst different defence failure scenarios.

Another example of structural flood defences potentially augmenting the damage from flood depth differential and velocity was witnessed in the Autumn 2000 floods in England (see [EA, 2001](#) for a description of these floods). Part of Keighley in Yorkshire was flooded by water from the River Aire. The structural flood defences of the adjacent but non-flooding River Worth held the water in the dwellings until the defences were deliberately breached, permitting the water to drain ([Kelman, 2001](#)). If this deliberate breaching had permitted the water to drain too swiftly, a property could experience a depth differential from the floodwater remaining inside or a high water velocity imposed by the water draining.

Property layout in a community influences the extent to which depth differential and velocity are manifest in a flood. [Lewis \(1979\)](#) notes that building layout, and even retaining damaged buildings, can assist in protecting communities. Similarly, [BB&V \(2001\)](#) write:

The extent, location and orientation of the various structures that have been constructed on the flood plain, both in Uckfield and in Lewes [both in the U.K.], made the effect of the 12th October 2000 flood worse than it would have been otherwise, by:

- increasing the amount and rate of surface water run-off, thereby increasing flows;
- reducing the area available for flood storage, thereby increasing peak levels;
- reducing the area available for flood flow conveyance, thereby increasing peak levels, contributing to rapid inundation and high flood velocities, and extending the period of flooding.

Contemporary hydrodynamic models have the capability of including property shape, size, and orientation for analysing a flood's depths, depth differentials, and velocities. This capability could be used during the design process, before existing buildings are retrofitted or before new buildings are constructed, for exploring the community layout which would minimise the flood actions impacting properties. The hydrodynamic models would thus be implemented as a community design tool for minimising flood vulnerability.

Awareness of how options affect the flood depth differential and velocity should lead to decisions which seek to diminish the detrimental impacts of these flood actions. Possible techniques include:

- Reducing slopes ([Figure 5](#)) to prevent sudden transport of water from one section of a community to another section. Dwellings might need to be built on the slope to avoid loss of development space, but properties are frequently built on slopes, indicating that this suggestion would not present a challenge.
- Creating green spaces designed as water storage areas for excess surface water. Underground storage areas could be considered too. Drainage patterns and

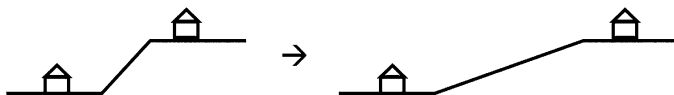


Figure 5. Reducing a slope to potentially diminish flood depth differential and velocity

property placement should lead surface water to storage areas without encountering properties. This solution prevents water rising swiftly outside properties and does not place properties in the pathway of surface runoff.

More detailed investigation would be essential before implementing these suggestions and they might require contingency plans. For example, any green space used for water storage would have a finite capacity. An event could overwhelm that capacity. Finally, impacts outside the realm explored here—in particular involving community safety, environmental impacts, other flood actions, and actions from other possible environment events or hazards—would need to be considered to ensure that diminishing the threat from flood depth differential and velocity would not exacerbate or create other concerns.

As before, choices are not provided here. Instead, issues are described and discussed to be certain that decisions can be made with an appropriate understanding of the consequences. Similar communities might view trade-offs in different ways leading to different decisions being made. These inconsistencies reflect differing collective needs and priorities.

5. CONCLUSIONS

This chapter has focused on the need for, and provided some simple tools for, understanding decision-making for flood-threatened properties. Rather than dictating individual and community choices, the approach is to transfer knowledge to people affected by floods so that they can make appropriate decisions for themselves—hopefully without causing or exacerbating other problems for themselves or others.

In this manner, the flood expert's role is that of facilitation rather than decision. The non-experts who suffer the consequences of, or who reap the rewards from, decisions are guided into understanding the issues and consequences, but are not told what to do. They take responsibility for themselves. This approach is termed “participatory” and “community empowerment”.

This focus has produced discussion which is principally qualitative, although it draws on quantitative results. Quantitative extensions could use techniques known as game theory, decision theory, optimisation algorithms, Bayesian games, and Monte Carlo Markov Chain methods. In Tables 11 and 12 probabilities could be assigned to flood parameter values and property owners' options while outcomes could be quantified as percent or monetary losses.

Multiple runs of models could provide probabilities of certain outcomes generating overall expected loss values within a given timeframe. They could also examine sensitivities of the results to incorrect or uncertain inputs or to maverick decisions, such as one property owner attempting to channel floodwater to their neighbour. Thus, scenarios could be compared quantitatively and a more apparently consistent and seemingly objective decision-making process would result.

The concern is that this quantitative approach yet again removes the decision and the needed understanding from the people affected. Furthermore, as implied with the estimated parameter in Kelman and Spence's (2003b) wall failure calculations,

quantitative outputs are only as good as the quantitative inputs and the analytical methods chosen.

Flooding is an emotional and challenging event for property owners. Translating and distilling research into useful tools can help to prevent a flood disaster even if a flood occurs. In respect of decision-making for flood-threatened properties, this chapter contributes to this process, although this material, and the policies and decisions resulting from it, must be considered in the context of flood types not covered by this chapter and other potential threats, short-term and long-term, to individual properties.

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CHAPTER 2

THE INFLUENCE OF FLOODPLAIN COMPARTMENTALIZATION ON FLOOD RISK WITHIN THE RHINE-MEUSE DELTA*

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Abstract: The present compartmentalization layout within the river polders in the Dutch Rhine-Meuse delta is the result of abandonment and partially removal of secondary dikes and the construction of modern infrastructure embankments. These structures will guide the flow of water in case the polder would inundate. Through the application of a 2D flood propagation model in the polder “*Land van Maas en Waal*” this study explores whether restoration or removal of old dike remnants would contribute to a reduction of the risk and damage during an inundation. A systematic set of 28 flood scenarios was simulated and for each scenario an additional damage and risk assessment was carried out. It is concluded that a simple removal or total restoration will not reduce flood damage, but that this must be achieved by a strategic compartment plan. With such a plan old dike remnants and present embankments can be used to keep water away from vulnerable and valuable areas for as long as possible and to guide the floodwater to areas that are considered less vulnerable

Keywords: flood risk, flood hazard, 2-D modelling, polders

1. INTRODUCTION

This study explores the role of historic and modern compartmentalisations on the potential damage resulting from inundation of river polders in the Rhine-Meuse delta. These polders are protected against river floods by primary dikes that are designed to prevent inundation for discharge peaks lower than the 1250-year

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recurrence time flood (or: annual probability of occurrence of 0.0008). For the Rhine this corresponds with a discharge of $16000 \text{ m}^3/\text{s}$ at the Dutch/German border and $3800 \text{ m}^3/\text{s}$ for the Meuse at the Dutch/Belgium border. However, since the magnitude of this design flood has to be determined by statistical extrapolation from a 100-year record of observations, there is a considerable uncertainty band around the estimated design discharge. Furthermore, it is anticipated that due to climate change peak flows in the Rhine and Meuse might increase during the forthcoming century (Middelkoop et al [2000]; Silva et al [2001]). For this reason, water management in the Netherlands considers a 'worst-case' scenario with an increase of the design discharge of the Rhine to $18000 \text{ m}^3/\text{s}$ and for the Meuse to $4600 \text{ m}^3/\text{s}$ (Silva et al [2001]). This rise in discharge implies that – when no measures are taken – the probability of overtopping or breaching of the dikes would increase as well and the safety of the polder and its inhabitants would fall below the required safety standard. Furthermore, there is a growing awareness that it is impossible to guarantee totally secure defence against floods: the inundation of river polders in the Netherlands therefore is no longer an unimaginable. Recently, the option of using retention areas outside the present high-water bed of the rivers is considered as flood reduction measure (Silva et al [2001]). Furthermore, the idea of appointing some river polders as temporary emergency retention basins has been put forward in order to alleviate flood risk in the densely populated and low-lying downstream parts of the Netherlands in case a flood higher than the design discharge would occur. To allow controlled flooding of certain polders, parts of the dike will be designed as spill-over that can withstand overtopping by large amounts of flood water without breaching. Before such decisions can be taken, the potential damage in different polders must be assessed, and measures to reduce damage in the eventual case of inundation must be thoroughly considered. This demands quantitative information on the hydraulic characteristics of the inundation process of a river polder, depending on the elevation, land use and the occurrence of embankments within the polder. These embankments subdivide a polder into different compartments, which greatly controls the rate and sequence of the inundation. The present-day compartmentalization of the polders consists of the remains of compartment dikes have been erected in historic times and embankment of modern infrastructure (highways, rail). Because of the effect of these embankments on the inundation, therefore, strategies to reduce the inundation damage of a polder should focus at the design of the compartmentalization layout to minimize the potential number of casualties and damage caused by the inundation.

The aim of this study was to determine the hydraulic characteristics (i.e. propagation rate, flow depth, inundation time) of the inundation of a river polder along the lower Rhine and Meuse rivers and the resulting damage, depending on the compartment layout of the polder. In addition to quantifying the effect of the present compartmentalization on the inundation propagation, we focused at assessing to what extent the inundation damage of river polders may be reduced by restoring the functioning of the old compartment dikes. For this purpose we simulated the inundation of a river polder using a two-dimensional flood propagation model for



Figure 1. Location of the study area

28 inundation scenarios. The scenarios are based on a set of seven different dike-failures including catastrophic breaches and controlled overtopping of different sections of the primary river dikes along the Waal and Meuse Rivers, and four combinations of modern and (restored) historic topographic layouts of the polder. Each inundation scenario was evaluated by assessing the potential damage caused by the inundation. The study was carried out for the polder “*Land van Maas en Waal*”, located between the Waal (the largest distributary of the lower Rhine River) and the Meuse River (Figure 1).

2. HISTORIC BACKGROUND

By nature, the Rhine-Meuse delta is characterized by alluvial ridges with natural river levees intersecting low-lying back-swamps. During periods of increased river discharge these swamps were flooded and remained inundated for a long period

due to poor drainage. The natural levees along the rivers consist mainly of sandy material and formed the natural higher ground in the area. When the first inhabitants entered the area, the levees were their natural choice for settlement and the starting point for the further development of the back-swamps. For protection against river flooding artificial mounds and dikes were constructed. The first dikes were built perpendicular to the natural levees, upstream from the settlement to divert the flood water around the settlement (Driessen 1994). The enclosure of the river area by dikes was completed between the 13th and 14th century. To exploit the agricultural potential of the back-swamps, the drainage was improved by digging a network of canals. Also, compartment dikes were raised within the polders to control drainage, and in the event of a dike breach, to prevent areas from flooding. Between the 16th and 19th century, a polder system was created surrounded by primary river dikes and with secondary dikes that formed closed compartments within the polder, each with its own drainage system of canals, sluices and pumps. The polder *Land van Maas en Waal* is a typical example of such a polder system (Figure 2). This defence system offered protection against smaller floods but it could not avoid that occasionally large floods overtopped or breached the primary river dikes (e.g., Driessen 1994). During the onset of the flood, the system of compartments diverted the flow of the floodwater and delayed the propagation by forcing the water to fill up the polder compartment by compartment (Hesselink et al 2003). This increased the time for evacuation and distributed the impact of the flood more evenly over the polder.

During the 20th century the condition of the main river channels and quality of the primary river dikes had greatly improved, and inundation of a river polder

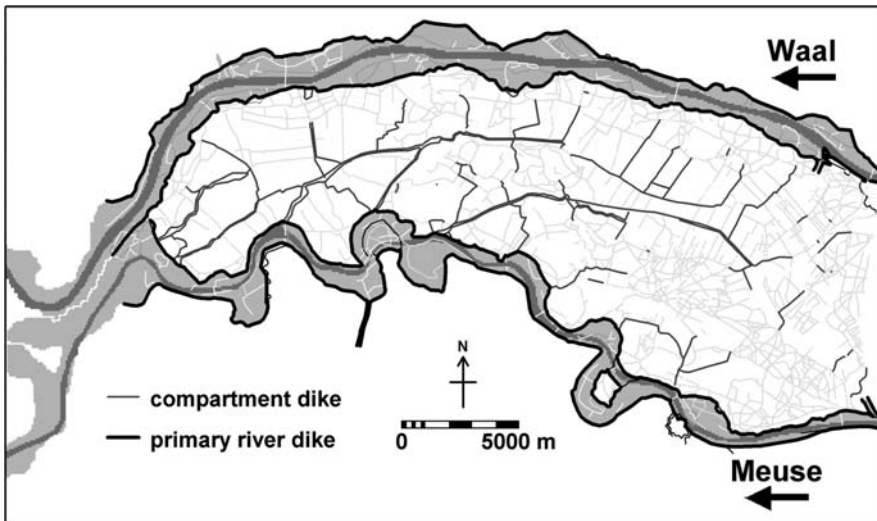


Figure 2. Historic map of the Land van Maas en Waal around 1850

in the Netherlands has not occurred since 1926. As a consequence, the appreciation and valuation of maintaining a secondary defence system within the polders declined and many compartmentalization dikes were subject of neglect or were completely removed. Large-scale development of the polder, with rapid expansion of urban and industrial area and land reallocation contributed to their decline. Embanked infrastructure gradually developed as additional compartmentalizing elements within the polder. This started in the late 19th century with railway lines and progressively developed in the 20th century with the construction of highways and motorways. Although these embankments were not designed as flood barriers, they will play a significant role in directing the floodwaters in case of inundation. Viaducts and bridges will funnel water and create increased flow-velocities. With the coinciding decline of the secondary dike system by end of the 20th century, the old compartment system was replaced by a non-systematic compartmentalization of the polder consisting of old dike remnants and new embankments.

3. INUNDATION SCENARIOS

The evaluation of the inundations was carried out for different combinations of failure of the primary river dikes and topographic layouts of the polder.

3.1. Dike Failures

A dike failure can be either a catastrophic breach or a controlled overtopping of the dike at a predetermined spill-over location. In total seven failures were simulated at five locations, five spill-overs and two breaches. Three locations are along the Waal river and two along the Meuse (Figure 3). At Weurt and Overasselt, both a breach and an overtopping were simulated. The choice for the locations was based on three considerations: 1) they are distributed more or less evenly along the rivers, so that differences between the scenarios will become sufficiently apparent; 2) they are not located too far downstream because that would result in very small inundations; and 3) they are positioned in between urban areas, because it would be unrealistic to construct a spill-over near a village. The location of Weurt for the breaching scenario was chosen because of the availability of historic data from the 1805 flood-reconstruction simulations carried out by Hesselink (2002).

3.2. Spill-Overs

The aim of a spill-over into a retention area is to cut off the peak of a flood wave in order to alleviate the flood risk in downstream areas. When compared to a dike breach, a spill-over allows controlled inundation over a pre-defined dike stretch, at an a-priori known flood stage in the river. As no scour hole develops, the amount of water entering the polder depends on the river discharge and eventual technical means to reduce the level of the spill-over threshold. To optimise the effect of the spill-over on reducing the downstream river flood stages, the peak of the flood wave

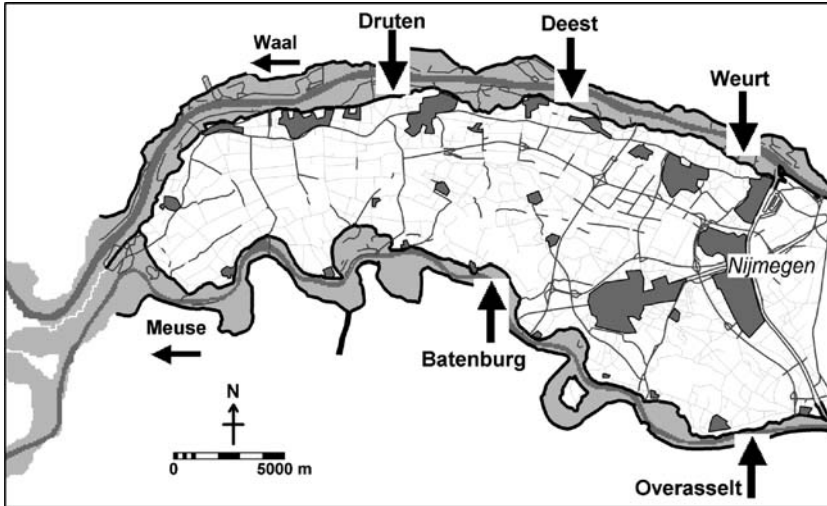


Figure 3. Location of the spill-overs and dike breaches

has to be cut off at exactly the right moment. In this study we considered a spill-over that will be activated as soon as the present-day design discharge of the Waal and Meuse rivers are exceeded, which is $10160 \text{ m}^3/\text{s}$ and $3800 \text{ m}^3/\text{s}$ respectively. At that moment the threshold height of the dike is reduced by 20 cm over a width of 525 meters for the Waal and 300 meters for the Meuse.

3.3. Breaches

The dimensions of the Weurt breach (i.e. gap width and scour hole depth, Figure 4) are based on the historic dike breach that occurred at this location in 1805. This flood disaster was reconstructed in detail by Hesselink (2002). The breach location along the Meuse river was selected near Overasselt since a dike breach occurred here in 1820 (Driessen 1994), although this event was not documented and analysed in the same detail as the 1805 flood. The dimensions of this breach and the scour hole were therefore not based on documentation, but on circumstantial evidence, like comparison with other Meuse dike breaches and shape of the reconstructed dike.

Apart from the ultimate dimensions of the dike breach, the rate at which the breach develops determines the amount of water flowing into the polder. In this study it was assumed that the final dimensions of the dike breach gap and scour hole were reached 3 hours after the dike collapsed.

3.4. Topography

Four different lay-outs of the polder interior were constructed, based on: A) a current Digital Terrain Model provided by the Province of Gelderland (Van Mierlo

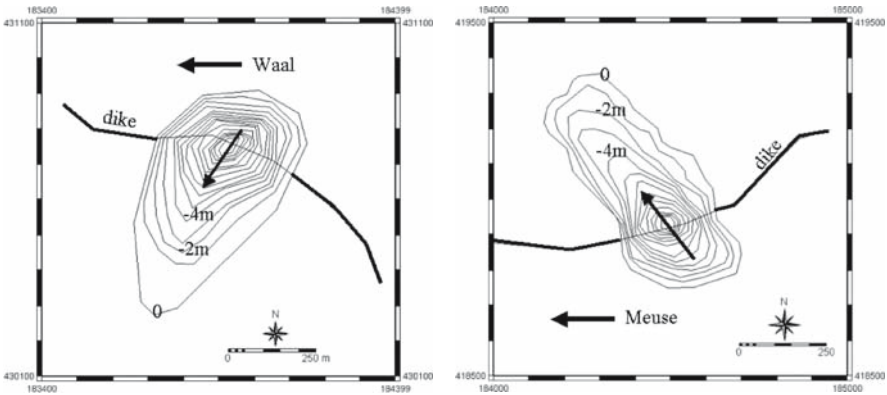


Figure 4. Dimensions of the dike breach near Weurt (left) and of the dike breach near Overasselt (right)

et al. (2001) and B) on the DTM of the polder as it was in the first half of the 19th century, reconstructed by Hesselink (2002) with a complete compartmentalization (Figure 5). The historic DTM is based on 35868 elevation points measured between 1950 and 1965 (before large land levelling and re-allocation schemes had taken place), complemented with data from a land survey carried out along five transects in the beginning of the 19th century and dike-height measurements carried out in 1801. The current DTM is derived from a laser-altimetric survey with a vertical accuracy of a few centimetres. Comparison between the topographic maps

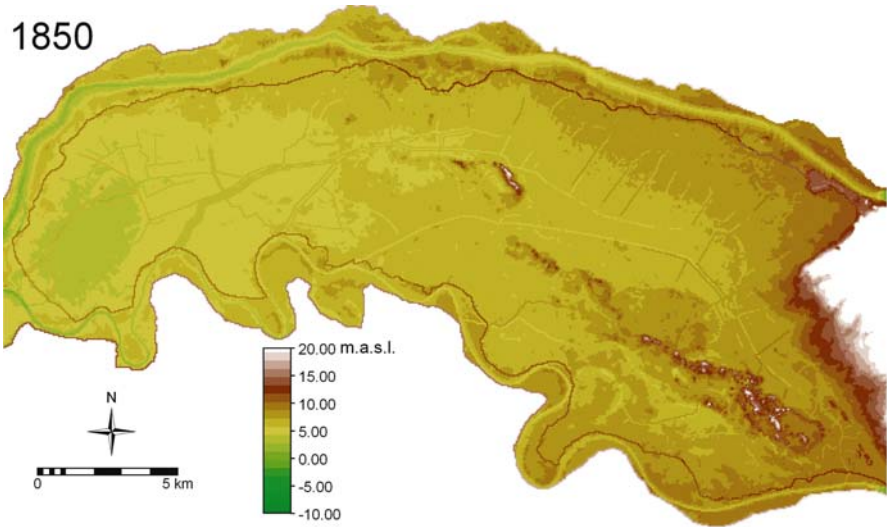


Figure 5a. Digital Elevation Model (DEM) of the study area around 1850

2000

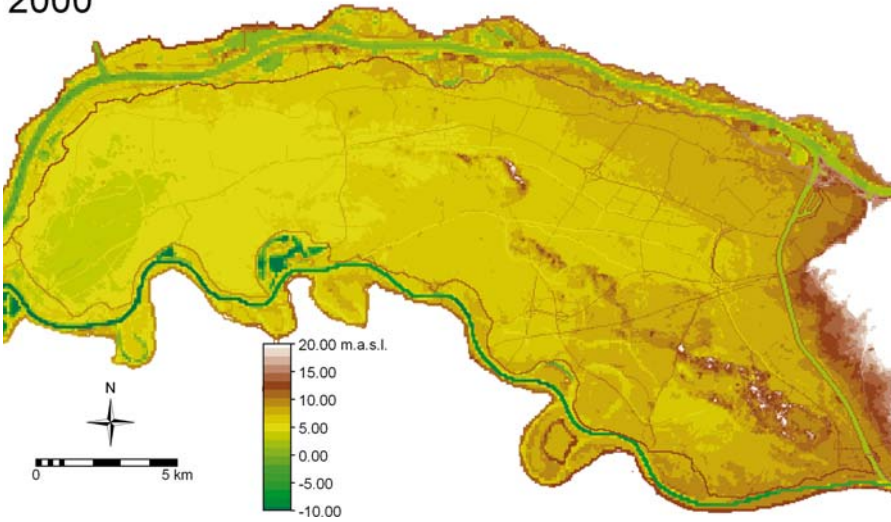


Figure 5b. Digital Elevation Model (DEM) of the study area around 2000

of 1850 and 2000 showed which former secondary dikes had disappeared and which remnants had survived. A field survey provided information of the height of these elements and of the embankments of modern infrastructure. For modelling purposes a grid size of 75 meters was chosen and a check with elevation points derived from

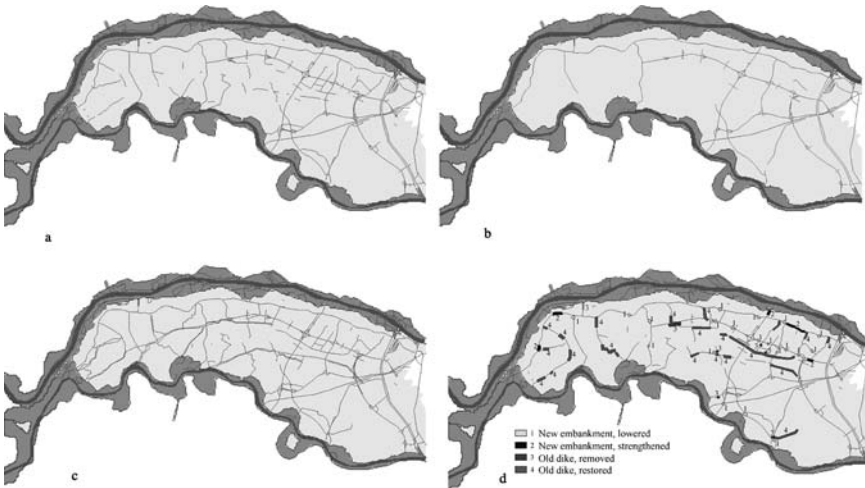


Figure 6. The 4 compartment layouts. Top-left: Present situation (A). Top-right: All old elements removed (B). Lower-left: All old elements restored (C). Lower-right: Strategic adaptations (D)

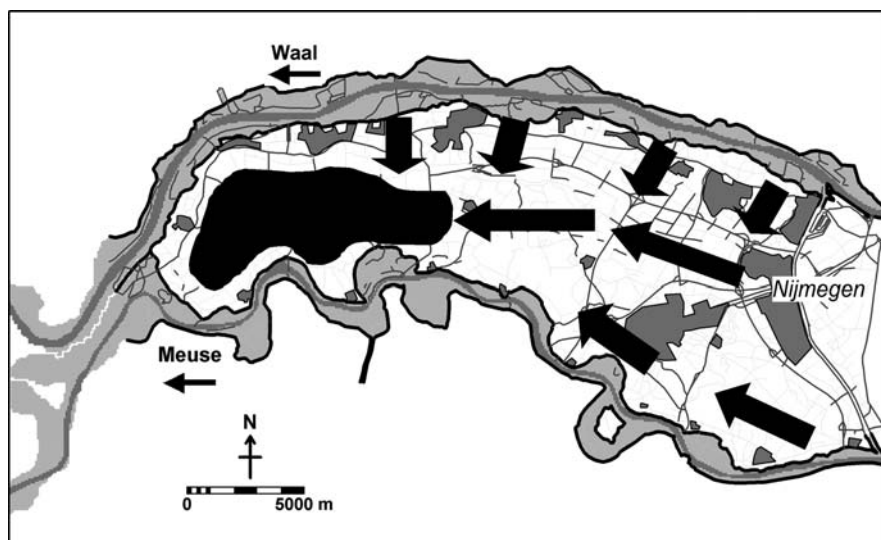


Figure 7. Strategic plan to use old and new barriers to keep the water away from vulnerable areas for as long as possible and to guide it towards less vulnerable parts of the polder

the topographic map showed that vertical accuracy was within 10 cm for 90% of the control points. The four different layouts are (Figure 6):

- A: Present situation, including dike remnants and modern embankments (present);
- B: Present situation with all remnants removed (cleaned-up);
- C: Present situation with the 1850 compartmentalization complete restored (restored);
- D: Present situation with strategic adaptations to protect vulnerable (urban) areas (strategic).

The aim of layout D is to reduce the impact of the flood in terms of damage or risk by selective changes in the present compartment layout. This involves both repair of previously removed dikes as well as removal of dike sections. The adopted strategy aims at directing the water flow away from, or around the urban areas and to guide it towards the less vulnerable agricultural areas in the centre of the polder (Figure 7).

4. THE 2D-FLOOD PROPAGATION MODEL DELFT-FLS

To assess the effects of linear elements within the polder on the flood characteristics, we used the two-dimensional flood propagation model Delft-FLS, developed at [WL | Delft Hydraulics](#) ([Stelling 1998](#)). This model was designed to simulate overland flow over initially dry land and through complex topography. It includes internal boundary conditions that allow the correct modelling of dike-breach scenarios, which makes it very suitable tool to simulate dike-failure related floods

in polder areas. The scheme used in Delft-FLS is based upon the following characteristics:

- The approximation of the continuity equation is such that a) mass is conserved, not only globally but also locally and b) the total water depth is guaranteed to be always positive which excludes the necessity of flooding-and-drying procedures;
- The momentum equation is approximated such that a proper momentum balance is fulfilled near large gradients.

The combination of positive water depths and mass-conservation assures a stable numerical solution. A proper momentum balance provides that this stable solution converges. The robust numerical scheme allows for the correct simulation of sub-critical and super-critical flow. Further information regarding the model properties can be found in [Stelling \(1998\)](#) and [Hesselink et al. \(2003\)](#).

4.1. Data Requirements

Delft-FLS requires the following information:

- An accurate digital terrain model (DTM) that includes all topographical features with their correct heights and depths, like dikes, embankments, channels, sluices, tunnels, etc.;
- Land surface cover information in terms of hydraulic roughness coefficients both for 'dry' (polder) and the 'wet' (channels) surfaces;
- Discharge or water-level time-series at the inflow boundary and a stage-discharge relation at the outflow boundary;
- Dimensions of the dike breach and their development through time.

All spatial data has to be available in raster format.

4.2. Model Output

The model produces three types of output: 1) raster maps at predefined time-steps that show the spatial distribution of the water depth and flow-velocity; 2) time-series at regular intervals of the water level and flow-velocity at predefined locations and discharges through predefined cross-sections; and 3) animation file showing the dynamic behaviour of the flood as it propagates through the polder.

4.3. Model Sensitivity

[Hesselink et al. \(2003\)](#) carried out a sensitivity analysis of inundation patterns simulated with Delft-FLS for varying surface roughness and topographic detail in the same area as the present study. They concluded that hydraulic roughness affects the speed at which the polder fills, but does not influence the maximum inundation depth. Furthermore, the model results were highly sensitive to the terrain topography and the inclusion of secondary compartment dikes within the polder. [Alkema and De Roo \(in press\)](#) tested the model on the inundation of the Ziltendorfer polder during the 1997 Oder flood in Germany. This polder is comparable in size and

land-use, although it is not as compartmentalized as the *Land van Maas en Waal*. The results of this study also confirmed the model sensitivity reliability, with the addition that for accurate water depth predictions a good discharge-stage curve is essential. These studies demonstrated that the Delft-FLS model is well capable of accurately simulating inundation depth and propagation rate of an inundation. Validation of other parameters, such as flow velocity, was not possible from these studies.

5. BOUNDARY CONDITIONS AND MODEL CALIBRATION

5.1. River Discharge

In accordance with the upper estimates of future design discharge (1250-yr recurrence time) due to climate change considered by Dutch water management (Silva et al. 2001) we carried out model simulations for a design flood equal to $18,000 \text{ m}^3/\text{s}$ for the Rhine at the Dutch/German border and $4600 \text{ m}^3/\text{s}$ for the Meuse at the Dutch/Belgian border. Assuming that the Waal River then discharges 63,5% of the Rhine discharge the corresponding peak discharge in the Waal River equals $11,400 \text{ m}^3/\text{s}$. The shape of this increased design flood wave was obtained from Dutch Institute for Water Management and Waste Water Treatment (RIZA, pers. comm., Figure 8). Likewise, the peak-discharge of the Maas will reduce as it travels downstream. Near the study area it is estimated that the peak discharge will be reduced by approximately $1000 \text{ m}^3/\text{s}$, giving a peak discharge of around $3650 \text{ m}^3/\text{s}$, but the width of the flood wave is much more stretched than further upstream (RIZA, pers. comm.).

5.2. Stage Discharge Relations Waal and Meuse

Stage-discharge relations of the Waal and Meuse Rivers at the downstream boundaries of the modelling area (villages of Opijnen and Empel) were provided by the water authorities of the Province of Gelderland (Figure 9). During the model

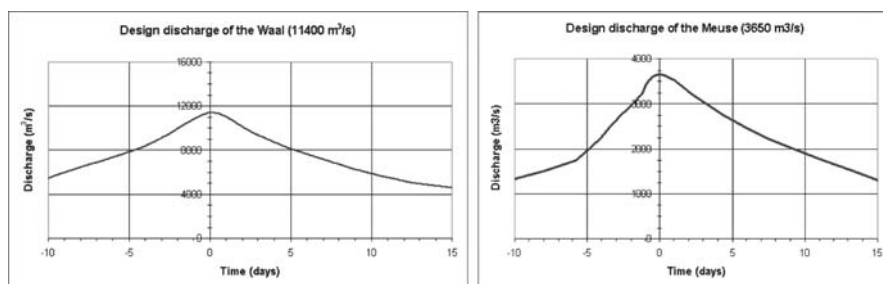


Figure 8. Discharge curve of the Waal used in this study (left) and that for the Meuse (right)

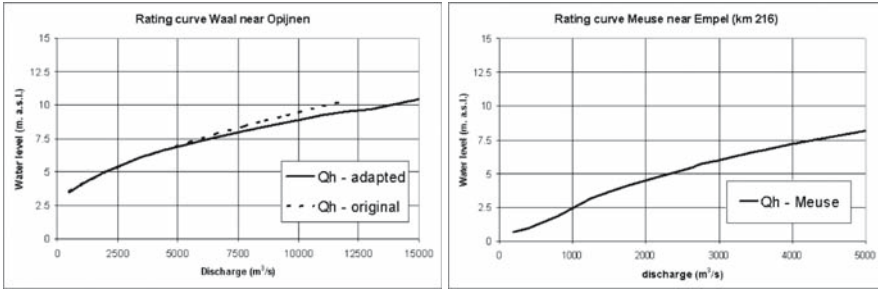


Figure 9. Stage-discharge curves for the Waal near Opijnen (left) and for the Meuse near Empel (right)

calibration the relation for the Waal River was slightly adapted to compensate for errors in the representation of the riverbed in the DTM. For the Meuse this was not necessary.

5.3. Surface Roughness Coefficients

The flow of water is hindered by the resistance of surface features. The surface roughness depends largely on the type of land cover and is often expressed as Manning's coefficient. Table 1 gives an overview of the land cover classes and the corresponding values of Manning's coefficients as they are found in literature (e.g. Chow 1959; Albertson and Simons 1964; Barnes 1967) with the exception of the values for the riverbed and the floodplain. The latter were obtained by model calibration and partially correct for inaccuracies in the representation of the riverbed. This explains their low values. Figure 10 shows the resulting surface roughness map.

5.4. Model Calibration

The discharges that are used as boundary condition in this study have never been recorded in the Waal and Meuse, so no measured water levels are available to calibrate the model. However, previous modelling studies have provided estimates

Table 1. Roughness values for different land cover types used in the model simulations

Land cover type	Manning's coeff.	Land cover type	Manning's coeff.
Riverbed	0.008	Heather	0.050
Floodplain	0.011	Main road	0.020
Urban area	0.100	Railway	0.020
Forest	0.150	Secondary road	0.015
Arable land	0.050	Water	0.012
Dike	0.030	Grassland	0.018

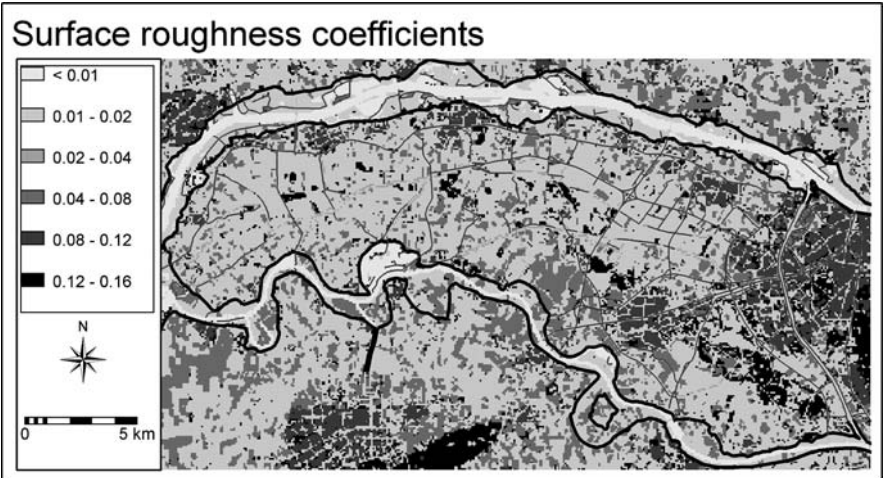


Figure 10. Manning’s surface roughness coefficients

Table 2. Comparison between water stage predictions of previous studies and the results of this study at various locations along the rivers

WAAL	Nijmegen (km885)	Bridge A50 (km894)	Druten (km904)	Ben. Leeuwen (km911)	Dreumel (km920)
Previous studies	15.00m	13.60m	12.50m	11.80m	10.80m
This study	14.99m	13.64m	12.48m	12.07m	10.93m
MEUSE	Heumen (km166)	Overasselt (km171)	Batenburg (km185)	Heerewaarden (km205)	
Previous studies	12.70m	12.00m	10.10m	7.30m	
This study	12.20m	11.90m	10.10m	7.54m	

of flood water levels in the rivers occurring at these extreme discharges (WL|Delft Hydraulics, pers. comm.). The outcomes of these studies were used to verify the water stages in the rivers calculated in this study (Table 2).

6. FLOOD HAZARD ASSESSMENT

The model results, hourly maps of flow-velocity and water depth, were transformed into seven indicator maps that describe the various aspects of a flood. For each of the 28 scenarios a set of these indicator maps was calculated. Figures 11a–g show such a set for a catastrophic dike breach near Weurt with the present topography.

All maps are the result of an aggregation of 150 hours of simulation time (150 hourly maps). Maximum water depth and maximum flow velocity were derived

Maximum water depth

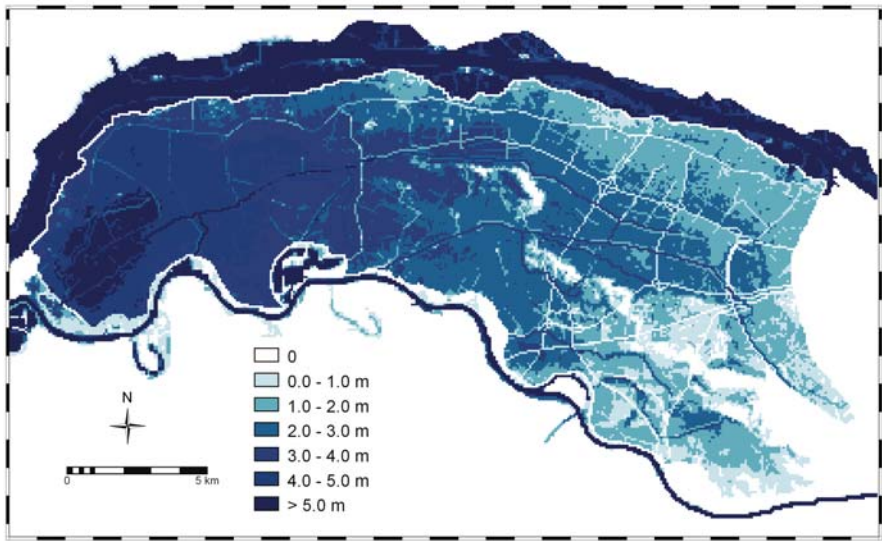


Figure 11a. Flood hazard indicator maps; Water depth

Maximum flow velocity

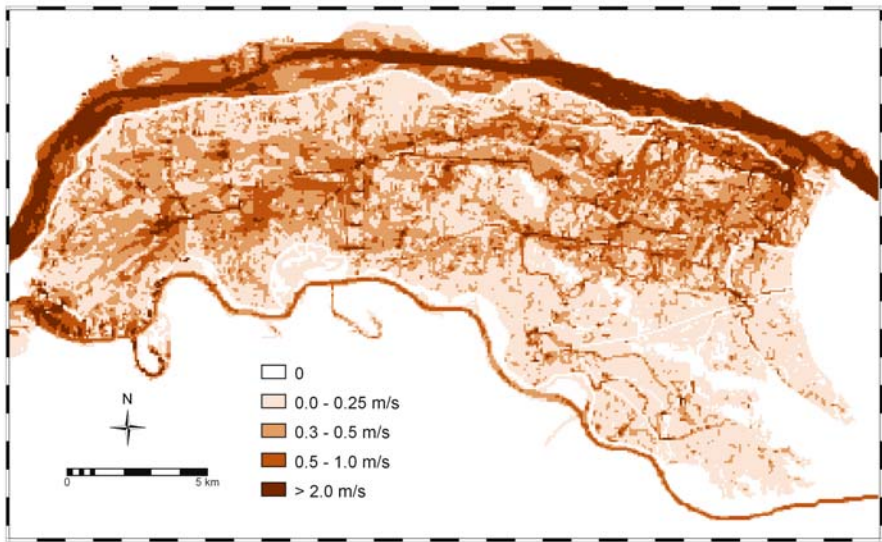


Figure 11b. Flood hazard indicator maps; Flow velocity

Maximum impulse

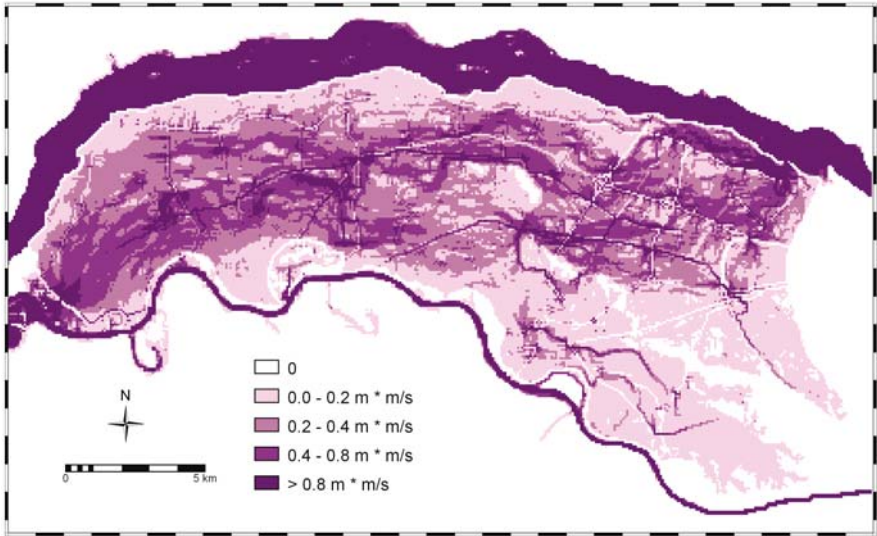


Figure 11c. Flood hazard indicator maps; Impulse

Maximum rising of the water level

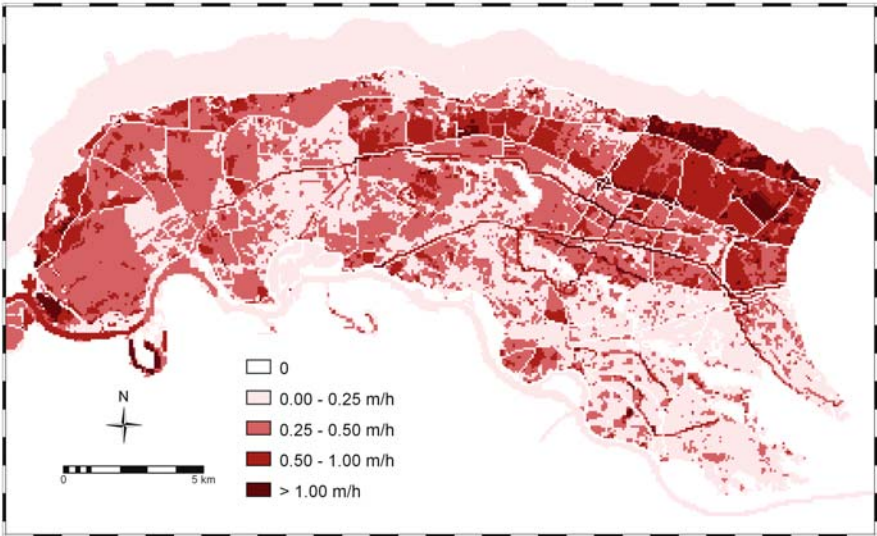


Figure 11d. Flood hazard indicator maps; Rising of the water level

Flood propagation

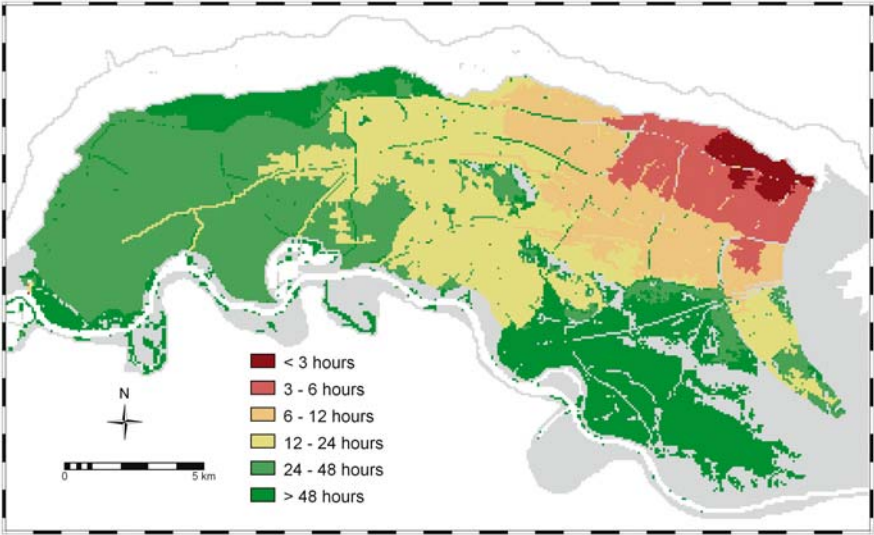


Figure 11e. Flood hazard indicator maps; Flood propagation

Estimated duration

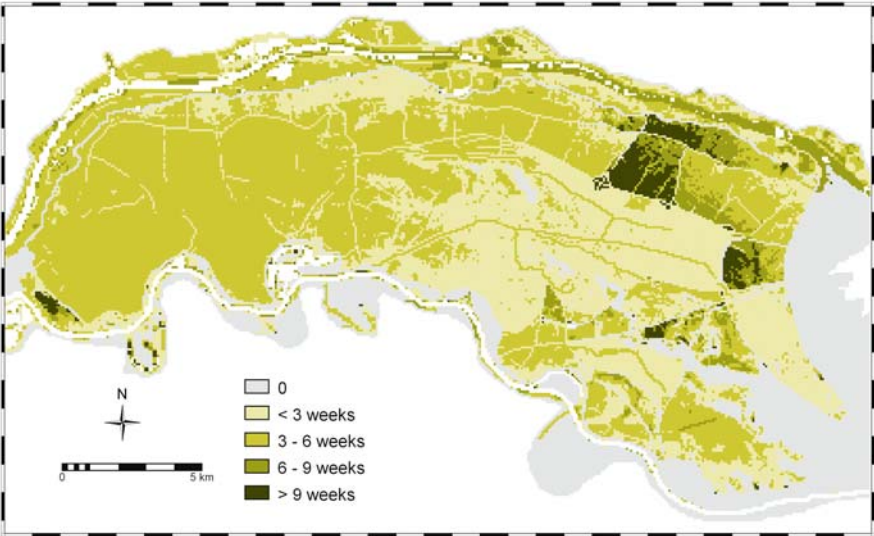


Figure 11f. Flood hazard indicator maps; Duration

Estimated Erosion / Sedimentation

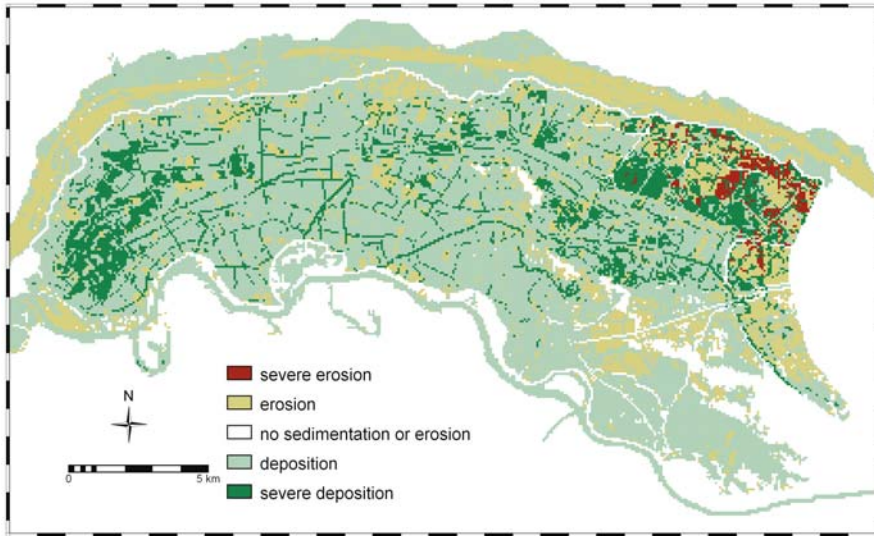


Figure 11g. Flood hazard indicator maps; Sedimentation / Erosion

directly from the water depth and flow-velocity maps that were generated by Delft-FLS. The indicator “impulse” was calculated as the product of the water depth and the flow velocity at each time step. It indicates the momentum of the water flow. The indicator “maximum rising” is based on the difference of water depth at a certain time step and the water depth at an hour earlier. It shows those locations where the water level will rise very quickly. The indicator map “flood propagation” shows how the floodwater moves through the polder and how barriers such as dikes and embankments diverted it. It gives an estimated time of arrival for the first floodwater in hours after the dike-breach. The indicator map “duration” is based on a natural draining of the polder near its lowest point (lower left corner, towards the Meuse river) through a 75-m wide gap in the Meuse primary river dike. The indicator map “sedimentation/erosion” gives a rough estimate on sedimentation and erosion rates. It is based on the Rouse criterion that gives the ratio between the upward lifting forces in the turbulent flow and the downward oriented gravitational forces. This criterion was calculated at the hourly time steps, for sediment particles with a diameter of $210\ \mu\text{m}$. Three additional assumptions were made: 1) The sediment-load of the water that has flown into the area decreases linearly with time; 2) The input of sediment at a certain location at a certain time depends on the amount of inflowing water and the change in storage; and 3) sedimentation and erosion occur only in the first 150 hours of the flood. This approach does not give absolute values for sedimentation and erosion, but provides an indication of where large accumulations may be expected.

7. FLOOD DAMAGE ESTIMATION

A standard way used to estimate flood damage is the so-called stage-damage curve, that describes for each land cover type the damage factor on a scale from 0 (no damage) to 1 (complete destruction) as a function of inundation depth (Figure 12). The absolute damage is obtained by multiplying the damage factor with the value of the unit.

In the Netherlands, a standardized method has been developed by the Directorate-General for Public Works and Water Management (Rijkswaterstaat) to estimate the possible monetary damage for flood scenarios (Kok et al. 2002). This method was applied to the 28 flood scenarios in our study. An example of the damage map is given in Figure 13. The summed-up totals for all scenarios are listed in Table 3.

7.1. Multi-Parameter Flood Hazard Estimation – An Example

Flood damage estimation methods based on depth-damage curves have several limitations. Firstly, there is usually lack of data to establish reliable curves. Secondly, the methods often only consider maximum water depth to estimate the damage, neglecting other relevant flood parameters, such as flow velocity, sedimentation and duration of the inundation. Thirdly, all consequences of the flood are expressed as monetary losses due to inundation, while aspects related to evacuation success, such as warning time and speed of the rising of the water level, are not considered. Therefore, a more elaborated impact assessment method was developed for this study that is based on the set of indicators that was calculated for each scenario (Figure 11: max. water depth; max. flow velocity; max. impulse; max. rate of water level rise; flood propagation time; flood duration). This approach is derived from decision support systems described by Beinat and Nijkamp (1998) and Van Herwijnen (1999).

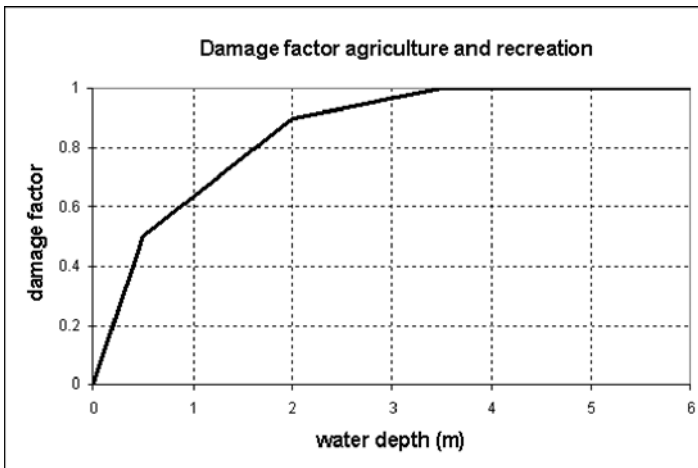


Figure 12. Stage-damage curve for agriculture and recreational areas (source: Kok et al. 2002)

Estimated damage - Method Rijkswaterstaat (Kok et al. 2002)

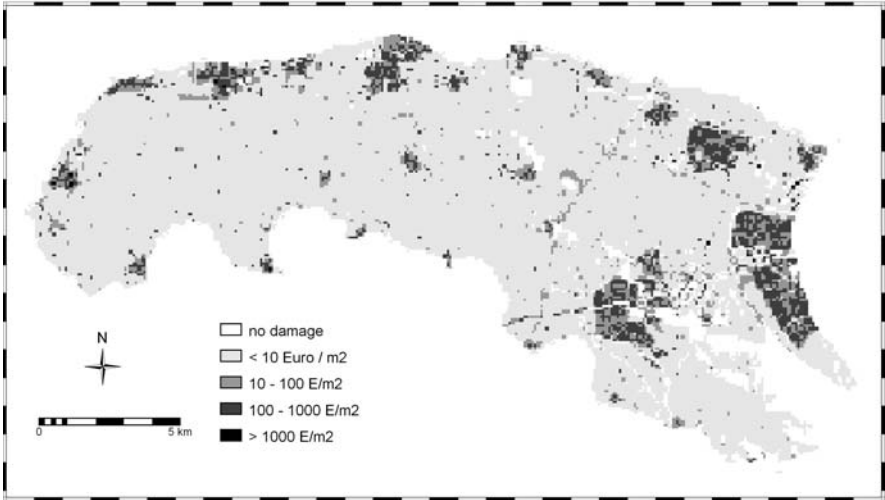


Figure 13. Flood damage map in Euros/m², based on the method of Rijkswaterstaat

Aggregation of the indicators was done in three steps: 1) Rescaling of the indicator value range to a normalized scale of 0 to 1; 2) Assigning weights to each indicator; and 3) Defining one of the scenarios as standard and to calculate for all other scenarios the ratio value. The process of normalization and weight assignment is subjective, but it is transparent. It includes more than one aspect of a flood and it allows a wider interpretation of the consequences of inundation than just damage (money). This approach does not provide absolute risk, damage or casualties values, but presents hazard classes on an ordinal scale where low classes stand for low hazard and high classes for high hazard. Table 4 shows the weights and normalised values for an example where six parameters were used for the assessment.

Table 5 presents the results of this multi-parameter hazard assessment. It shows the aggregated total hazard values for all scenarios as ratio of the standard scenario, based on the assumed weights indicated in table 4.

Table 3. Overview of flood damage for the 28 scenarios (in million Euros)

Type		Present situation (A)	Cleaned-Up situation (B)	Restored situation (C)	Selective changes (D)
1) Weurt (Waal)	Breach	5400	5300	5500	4300
	Spill-over	1900	1700	2000	905
2) Deest	Spill-over	740	740	761	711
3) Druten	Spill-over	627	629	645	588
4) Overasselt (Maas)	Breach	2600	2600	2700	2500
	Spill-over	1400	1400	1400	1300
5) Batenburg	Spill-over	859	906	907	946

Table 4. Example of normalizing and weighing a set of flood hazard parameters (weights are between brackets)

Water depth (0.2)		Impulse (0.2)		Rising (0.1)	
class	value	class	value	class	value
[m]	[-]	[m ² /s]	[-]	[m/h]	[-]
0	0	0	0	0	0
0.0–0.2	0.1	0.0–0.1	0.1	0.0–0.1	0.2
0.2–0.5	0.25	0.1–0.2	0.2	0.1–0.3	0.4
0.5–1.0	0.5	0.2–0.3	0.4	0.3–0.5	0.6
1.0–1.5	0.7	0.3–0.4	0.6	0.5–0.75	0.8
1.5–2.5	0.85	0.4–0.8	0.8	0.75–1.0	0.9
2.5–3.5	0.95	>0.8	1	>1.0	1
>3.5	1				
Duration (0.1)		Sedimentation (0.1)		Propagation (0.3)	
class	value	class	value	class	value
[weeks]	[-]	[-]	[-]	[hours]	[-]
0	0	severe erosion	1	0	0
<2	0.2	medium e.	0.85	<3	1
2–4	0.4	light e.	0.7	3–6	0.8
4–6	0.6	equilibrium	0.5	6–12	0.6
6–8	0.8	light depos.	0.7	12–24	0.4
>8	1	medium depos.	0.85	24–48	0.2
		severe depos.	1	>48	0.1

Table 5. Comparison of the aggregated relative hazard values for all scenarios. The scenario with a breach at Weurt and the present topography is used as standard

	Type	Present situation (A)	Cleaned-Up situation (B)	Restored situation (C)	Selective changes (D)
1) Weurt (Waal)	Breach	1	0.98	1.01	0.89
	Spill-over	0.46	0.45	0.50	0.35
2) Deest	Spill-over	0.32	0.32	0.34	0.31
3) Druten	Spill-over	0.23	0.24	0.24	0.20
4) Overasselt (Maas)	Breach	0.63	0.64	0.65	0.59
	Spill-over	0.4	0.40	0.41	0.37
5) Batenburg	Spill-over	0.33	0.35	0.35	0.33

8. RESULTS AND CONCLUSIONS

The results of 28 flood scenarios in terms of damage and relative hazard are shown in Tables 3 and 5. From these tables can be seen that the further downstream the failure locations are situated, the lower the damage and hazard because a smaller part of the polder is flooded. Failure at the most upstream located point of the polder

will result in the highest damage. Furthermore, the damage and hazard associated with a catastrophic dike breach are significantly higher than in case of a spill-over inundation. The breaching of the dike creates an enormous gradient between the water level in the river and the low-lying polder surface. This results in a much higher flux of floodwater into the polder than of a controlled overtopping at a spill-over location. So from a safety and damage reduction point of view it can be concluded that it makes sense to prefer controlled overtopping over catastrophic breaching. Embankments and internal dikes not only control the inflowing flood water, but also create storage locations that drain badly and could extend the inundation time up to 2 months.

Comparison between the different topographies showed that the complete restoration of the old secondary dike systems does not result in a significant improvement, not for the damage nor for the hazard. The same holds for the scenarios where all the old dike-systems were removed. There are two explanations for this: 1) Most secondary dikes are too low to block the water flow completely and therefore do not affect significantly the maximum water depth in the polder. Especially for methods that only use the maximum water depth as hazard indicator, like the method of Rijkswaterstaat, the results will be similar. 2) Compartmentalizing has both positive and negative consequences. Inside the compartment the water level will rise faster and the maximum water depth may be higher than without the compartmentalization. Outside the compartment there will be a delay in the arrival time of the floodwater (or no flood at all) and the flow-velocities will be reduced. Whether the positive consequences outweigh the negative ones depends on the distribution of vulnerable (and valuable) areas – e.g. urban areas – in relation to the compartments. In the scenarios that consider the complete restoration or removal of old dikes the positive effects are balanced by the negative consequences. In the D-scenarios a strategic plan was developed with the aim of guiding the water away from the vulnerable urban areas where a lot of valuable property is concentrated. The water was guided to the more rural parts of the polder. This strategic approach does reduce the damage or hazard in the inundated area. It can therefore be concluded that complete restoration or removal will not improve the safety situation in the polder, unless a strategy is followed to protect the more vulnerable parts. Instead, this can be achieved by a well-designed compartment layout, comprising both modern and (repaired) historic embankments.

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CHAPTER 3

OSIRIS – AN EXAMPLE OF CITIZEN-ORIENTED TECHNOLOGY DEVELOPMENT IN THE AREA OF DISSEMINATION OF INFORMATION ON FLOOD RISK MANAGEMENT

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Abstract: In consequence of dramatic flood events in Europe at the end of last century, a request for more efficient information and communication systems and procedures at all stages of the flood risk management process was clearly identified. Current trends in the flood warning and forecasting system design are more concerned by the improvement of observation capacity and the efficiency of a forecast, less by the proper dissemination and reception of the information by the different stakeholders of an inundation crisis. Operational Solutions for the management of Inundation Risks in the Information Society (OSIRIS) is an example of a user demand-driven European RTD Project, which exploits concept of citizen-oriented technology development in a crucial area of flood risk management. This was also the *raison d'être* of the OSIRIS. The project aimed at satisfying the principle of the access to strategic environmental information by citizens. It allowed testing how implemented new technologies incite to proactive attitudes and behaviour in the terms of reduction of vulnerability and in the context of flood risk management

Keywords: flood warning, flood risk communication, information and communication technology (ICT)

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1. INTRODUCTION

In this chapter is presented the expertise and lessons learned on the flood risk management acquired through recently completed (March 2003) project Operational Solutions for the management of Inundation Risks in the Information Society (OSIRIS). Partly funded by the European Commission as the User-Friendly Information Society Project IST-1999-11958, OSIRIS was awarded under the 5th European Community Framework Programme covering Research, Technological Development and Demonstration activities.

Initiated in January 2000, as a reaction to catastrophic floods in the Oder (Odra) basin in 1997, OSIRIS tried to exploit a social dimension of technological development in a crucial area of dissemination of information in all phases of flood risk management. The pertinence of the problem although recognized in the relevant literature (Platz, 2002) was unfortunately confirmed by dramatically high toll of human lives lost during flood events in 2002 in Europe (Gardon – 35, Elbe – 25).

In fact, the *raison d'être* of the OSIRIS is a request for more efficient information and communication systems and procedures at all stages of the flood risk management process.

Current trends in the system design are more concerned by the improvement of observation capacity and the efficiency of a forecast, less by the proper dissemination and reception of the information by the different stakeholders of an inundation crisis. OSIRIS is an example of a user demand-driven project, which exploited a concept of citizen-oriented technology development in a crucial area of flood risk management, aiming at satisfying the principle of the access to strategic environmental information by citizens. It allowed testing how implemented new technologies incite to proactive attitudes and behaviour in the terms of reduction of vulnerability in the context of flood risk management.

2. THE OSIRIS CONTEXT OF THE FLOOD RISK MANAGEMENT

Recent catastrophic floods in Europe (Oder in July 1997, Aude and Herault in November 1999, Elbe in August 2002 and Gardon in September 2002) demonstrated clearly a serious lacks in the process of flood warning dissemination (Erlich et al., 2000). In Poland, the 1997 flood exposed the fragility of the system of communication between all the stakeholders involved: meteorologists, hydrologists, civil security organizations and army, let alone between the national flood control centre and the population at large. In the case of flash flood events, specific for a Mediterranean arc, they resulted during last years in numerous victims amongst car drivers.

During the Oder flood, the lack of information issued by the authorities only served to enhance the importance of the media (especially local radio and TV stations), which broadcast information round the clock though often without giving an overall view of the problem. In Poland, as a reaction to a deficient information dissemination system, an unprecedented phenomenon occurred thanks to

the communication potential of the Internet. In response to a pressing need for information on how the situation was evolving locally and regionally in the flooded areas, about 100 dedicated web sites were created in Poland during 2–3 days of July 1997. At varying stages of the crisis, these sites issued information that might be classified as follows:

- More efficient information and communication systems and procedures are required at all stages of the flood risk management process. In this respect, appeals for help (for emergency medical services, medicine, vaccines, etc.);
- appeals for volunteers (to reinforce and monitor dykes or take part in operations to save cultural heritage objects in museums and university libraries);
- requests for information on people in flooded areas;
- lists of people evacuated, with the precise locations of temporary shelters;
- miscellaneous information (weather, photographs, maps of flooded areas, safety instructions, rules for avoiding intoxication, road information, etc.);
- appeals to people with mobile phones to transmit information on the situation as it evolved on the ground (street by street, locality by locality);
- appeals to the police and army to protect shops against pillaging and vandalism;
- appeals to the administrators of other sites to act as relays for servers deprived of electricity;
- appeals for humanitarian aid.

This unique example of a spontaneous initiative by civilians was confirmed on other occasions of catastrophic flood events elsewhere and has inspired the OSIRIS consortium members composed of 13 organizations from five European countries (France, Germany, Poland, Italy and the Netherlands). A multi-disciplinary team, composed of specialists in flood forecasting systems, organization, management and information systems, psychologists, sociologists and economists was gathered. The partnership was built around three groups, including representatives of end users (including crisis situation decision-makers), researchers and consultants:

- Catchment area managers and citizens' representatives (municipalities or local area associations);
- Research organizations;
- Service companies.

The basis idea behind OSIRIS consists in development of appropriate solutions adopted to specific conditions and crisis situations not as an alternative to the existing professional channels for information dissemination but as an complementary tools that may solve the encountered drawbacks.

3. THE EXPERIENCE OF OSIRIS

3.1. Objectives of the Project

More efficient information and communication systems and procedures are required at all stages of the flood risk management process. In this respect, emergent information and communication technologies can contribute significantly. Therefore, the

OSIRIS’ main objectives were directly driven by an important and urgent need to develop systems able to increase the awareness of citizens concerning inundation risks, as well as their required involvement in the prevention and crisis management process;

- Prepare the citizens and crisis managers to efficient protection and rescue actions during inundation crisis periods;
- Improve the relevance and quality of the information made accessible to all flood crisis stakeholders (crisis managers, rescue civil protection organizations, citizens) before, during and after the crisis period;
- Organize efficient post-crises assessments and disseminate their results.

The very purpose of the OSIRIS project was to identify such contributions, to develop, implement and to test their feasibility on the basis of the prototyped applications.

3.2. Methodological Approach

The Project was organized in three phases: design, development and validation (Figure 1).

Based on the analysis of the needs of the stakeholders and taking into consideration the basic principles of OSIRIS project, orientations for a relevant information

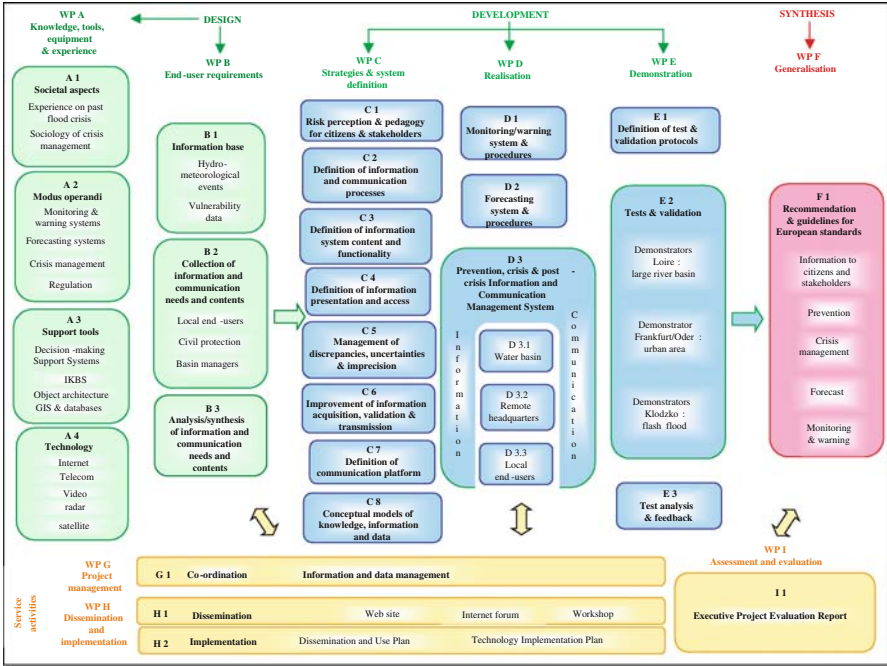


Figure 1. OSIRIS methodological approach

and communication strategy were defined. The project started from analysis of the existing situation. Three sites from engaged partner countries had been selected to study the given state of the situation:

- Frankfurt/Oder (Germany);
- Klodzko region (Poland);
- Middle Loire basin (France).

The pilot sites are believed to be representative for the European situation as they are covering a wide variety of aspects with respect to climate, topography, hydraulic environment, and administrative structures, riparian needs, cultural background and history.

The sites characteristics are summarised in Table 1.

A part of OSIRIS project activity was dedicated to search for efficiency in translating the information concerning flooding in a warning message and disseminating it through various channels, with proper feedback mechanisms, so that this information is properly received, understood and used (Figure 2) (Blancher et al., 2003).

OSIRIS tried to demonstrate that information and communication technologies can be used to improve not only flood forecast, their traditional field of application, but also flood warnings dissemination and reception. Therefore, an important part of OSIRIS project was devoted to properly understand the socio-political and cultural contexts of both risk communicators and their audience. This was achieved through enquiries of all categories of end-users (crisis managers, water basin managers, rescue civil protection organizations, county representatives and citizens). For this purpose, an extensive programme of field survey in three pilot basins was conducted on the experience and expectations of different end-users: institutional stakeholders (administration, police and fire brigades) and local authorities in charge of floods management at the municipality level, inhabitants, farmers and firm managers (Blancher et al., 2001).

The first year of the project was devoted to understand potential end-users needs, through proper study of their psychological attitude, social context, problems encountered because of inundations, attitudes towards different information and communication technologies, etc. In-depth surveys – through individual and group

Table 1. OSIRIS demonstrator sites characteristics

	Hydraulic situation	Warning lead time	Flood seasons	Administration	Settlement	Last flood damages
Frankfurt	Lower part of river basin	days to week	spring summer	federal decentralised country wide	city	1997
Klodzko county	Upper range of river basin	minutes to hours	mainly summer	governmental: nationwide self-governmental: decentralised	cities and rural areas	1997, 1998
Loire	middlerange of river basin	hours to days	winter	centralised hierarchical	rural districts	2000

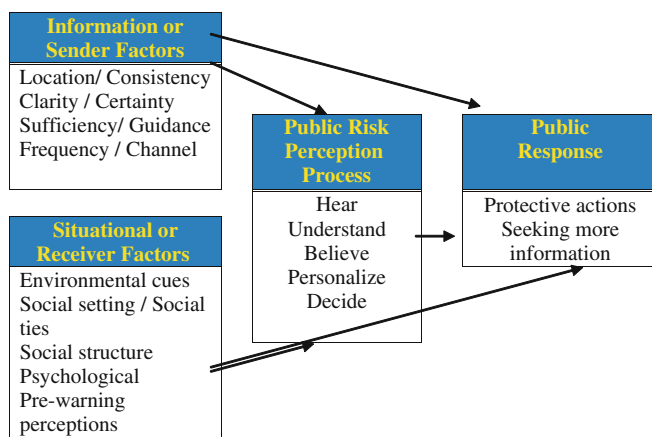


Figure 2. A Model of the Theory of Public Risk Communication. [Fitzpatrick C. and Mileti D.S.] [1994]

interviews (focus groups) or questionnaires – were conducted in the pilot sites in France, Poland and Germany.

The analysis of the existing situation at the three different sites concerned the knowledge available about the hydraulic/hydrological system, the structure of administration and its way to manage inundations as well as the support tools available for prevention and rescue as well as the technology applied. The main results of the investigations are the following:

- Citizens are reluctant in accepting official forecast on floods;
- Citizens want better information and preparedness to flood event;
- Information from administration officials should be strengthened.

On the basis of identified requirements of stakeholders and analysis of data sources available in three pilot basins, a general purpose OSIRIS policy was drawn up. It allowed to propose the final end-users a methodological approach for selecting the appropriate solutions to be developed, implemented and tested in the framework and time limits of the project.

As a result the project specification phase consisted in designing the tools and approaches to support the entire cycle of risk management, respecting also one of the project aims of satisfying the principle of the access to a strategic environmental information by citizens.

Based on the analysis of the needs of the stakeholders and taking into consideration the basic principles of OSIRIS project, orientations for a relevant information and communication strategy were defined.

3.3. Results of OSIRIS

The OSIRIS Project generated five operational *software* prototypes (demonstrators), which are implemented in the pilot basins of the Loire (L1, L2), Nysa Kłodzka (K1, K2, K2A) and Frankfurt/Oder (F) rivers. The main principles of these prototypes

are available for viewing on the front page of the OSIRIS web site (<http://www.ist-osiris.org>).

The OSIRIS project produced also a certain number of *documents* (Deliverables, reports and notes) containing among other description of methods, methodologies or results of investigations (e.g. the manner to conduct a field survey). Some of them, having public character, can be downloaded from the OSIRIS site.

3.4. OSIRIS Demonstrators and Lessons Learned

The definition of end user requirements revealed significant differences between the sites Frankfurt/Kłodzko/Loire.

- **Frankfurt:** After reunification, the legal system and organizational structure changed. Many services and procedures have to be redefined, and new tools/services created. Transboundary collaboration with Polish partner city Ślubice on the opposite bank of the river Oder/Odra is operational and has to be strengthened through mutual exchange of information and resources.
- **Kłodzko:** After the floods in 1997 and 1998, crisis managers realized that the nation-wide hydrometeorological service did not cover (and cannot cover) small scale/region systems with extremely short lead-time for flash floods sufficiently. In consequence, the municipality of Kłodzko decided to build up its own local crisis management center integrated within the nation-wide services. Recommendations from OSIRIS project are being considered, and the IMGW (Institute of Meteorology and Water Management), administrating the network and hydrological and meteorological forecasting, develops new services directed to small localities.
- **Loire:** Crisis management and flood forecast are institutionalized, because long and existing systems and services are implemented and operational. Recommendations from the OSIRIS project, in particular concerning wider dissemination of information, will be considered, however, changes will be made gradually.

The diversity of inundation management systems as formed in the three sites is assumed to be a characteristic within the European context. To implement these orientations, OSIRIS has conceived five potential prototype solutions (called also 'projects') to be developed. These results support a strategy of strengthening ICT (Information and Communication Technology)-based solutions within the project. Moreover, they substantiate the argument that the mobility relates to information.

3.4.1. *Demonstrator Frankfurt/Oder (F): 'Frankfurt flood information and communication management'*

In the present situation, the flood risk management in Frankfurt (Oder) is not ICT supported. The involved actors have to cope with heterogeneous information resources with a variety of proprietary formats. The information resources are distributed at different places and are maintained and owned by different authorities. The objective of the demonstrator F (www.ist-osiris.org/ffoder) in Frankfurt (Oder)

is the development of a web-based platform connecting the different and distributed information sources accessible by all groups of end users. The basic idea is the design of a meta-information system with functionalities for information content presentation and communication (Holz, 2003).

The site Frankfurt/Oder is an example for open access to all kind of information content and services during all phases of pre-at-post crisis situation.

The demonstrator allows access to primary and secondary information resources via Internet. It supports the typical decentralized organization of crisis-involved organizations and authorities in a federal community as Germany. The demonstrator by architecture is basically document-oriented avoiding central administration of data bases. It reflects the situation of limited human resources and few background on ICT environment within the crisis management organization (fire brigade).

The information contents to be implemented in the Frankfurt Flood Information and Communication Management (FICOM, Figure 3) demonstrator concerns the following ICMS content types:

- topography/bathymetry of the area,
- infrastructural information of the area,

Donnerstag, 20. März

► **Home**

► **Nutzerhandbuch**

► **Neuigkeiten**

► **Hochwasser**

► **Wetter**

► **Dokumente**

▼ **Weiteres**

Web Services
Präsentation
Bürgerumfrage
Impressum

FRANKFURT
(Vorhersage für 21.03.2003)

bewölkt
-5 bis 6 °C

mehr Wetter? [Klimatage.com](#)

(Pegelanzeige/-vorhersage)

Datum 19.03.2003

Zeit 18:15

Pegel 329 cm ➔

Alarmstufe keine

Operational Solutions for the management of Inundation Risks in the Information Society

Willkommen auf dem OSIRIS Demonstrator Frankfurt (Oder) / Slubice
Dieser Demonstrator enthält wichtige Informationen zum Thema Hochwasser und Hochwasserschutz in Frankfurt (Oder) und Slubice.
[Mehr...](#)

Der Demonstrator hat ein neues Design. Noch mehr Informationen, schnellerer Zugriff und verbesserte Werkzeuge helfen dem Benutzer, sich noch schneller und besser auf dem Server zurechtzufinden.
[Mehr...](#)

Lernen Sie durch Mithilfe Hochwasserkatastrophen organisiert zu meistern.
[Mehr...](#)

Eine Kurze Einstiegshilfe zur Arbeit mit dem Server können Sie in der Demonstratorbeschreibung finden.
[Mehr...](#)

Das Pegelanzeige und -vorhersage Tool bietet die Möglichkeit erwartete Wasserstände der nächsten Stunden bis Tage zu bestimmen...
[Mehr...](#)

Das Ziel des OSIRIS-Projektes ist die Analyse der Organisationsstrukturen und Verfahren eines einheitlichen Hochwasserschutzes in großen Einzugsgebieten...
[Mehr...](#)

Demonstrator Hilfe ?

City of Frankfurt/Oder (FFO) Germany

Märkische Oderzeitung
aktuelle Nachrichten aus der Oderregion

City of Slubice (Poland)

OSIRIS project

German Menu Polish Menu English Menu

BAU N F

Figure 3. Interface of the Frankfurt Flood Information and Communication Management (OSIRIS Demonstrator F)

- meteorological and hydrological situation in space and time,
- risk exposure of people/objects/infrastructure and their accessibility in space and time,
- resources for prevention/rescue actions in space and time,
- actions to be taken (management),
- education/training/entertainment.

Two information access terminals on German and Polish side of the Oder were implemented.

3.4.2. Demonstrator Kłodzko1 (K1): 'Information and Education Web-site'

The solution of the Internet portal of education support system (K1) is intended to reinforce warning system effectiveness via dissemination of information regarding how the system works and what action to take during a flood (http://www.ist-osiris.org/extern/mockup/index_k1.html).

The project's objective of the K1 system is to execute and implement a system for the distribution of common information through the Internet. Basic goals are:

- To ease access to information in the field of flood loss limitation on a local (community) and individual (residents, firms) scale.
- The enabling of various agencies (governments, schools, firms, NGO, residents) to disperse their own experiences in the field of flood loss limitation.
- The enabling of confirmation of individual knowledge in the domain of flood loss limitation with the aide of tests from chosen fields.

For achieving these goals, the K1 system collects managed information resources in K1 specific data structures. In that sense, the K1 application-specific contents deal with the education and training category, defined in the generalized ICMS information content description, aggregating various resources (Figure 4).

However, its main objective is to propagate a 'prevention culture' philosophy – conscious flood preparedness based on understanding of this phenomenon (Konieczny and Cunge, 2003).

3.4.3. Demonstrator Kłodzko2 (K2): 'Local-Level Decision-Making Aid Tool'

The warning support system (K2) is meant for the county crisis intervention centre (http://www.ist-osiris.org/extern/mockup/index_k2.html). It is intended to facilitate coping with the problem of forecast uncertainty (Price and Maskey, 2003) and assurance of early notification of crisis intervention forces in the area and warning dissemination to inhabitants regarding the present danger. The forecast results and the threshold values compiled in a data base (river water level, amount of precipitation) representing dangerous situations facilitate decisions regarding notification of forces or warning of inhabitants using various forms of communication (fax, stationary or mobile telephone and mass telephone notification). This demonstrator is built of two connected sub-systems: K2, Local-Level Decision-Making Aid Tool, and K2A, Mass telephone notification system.

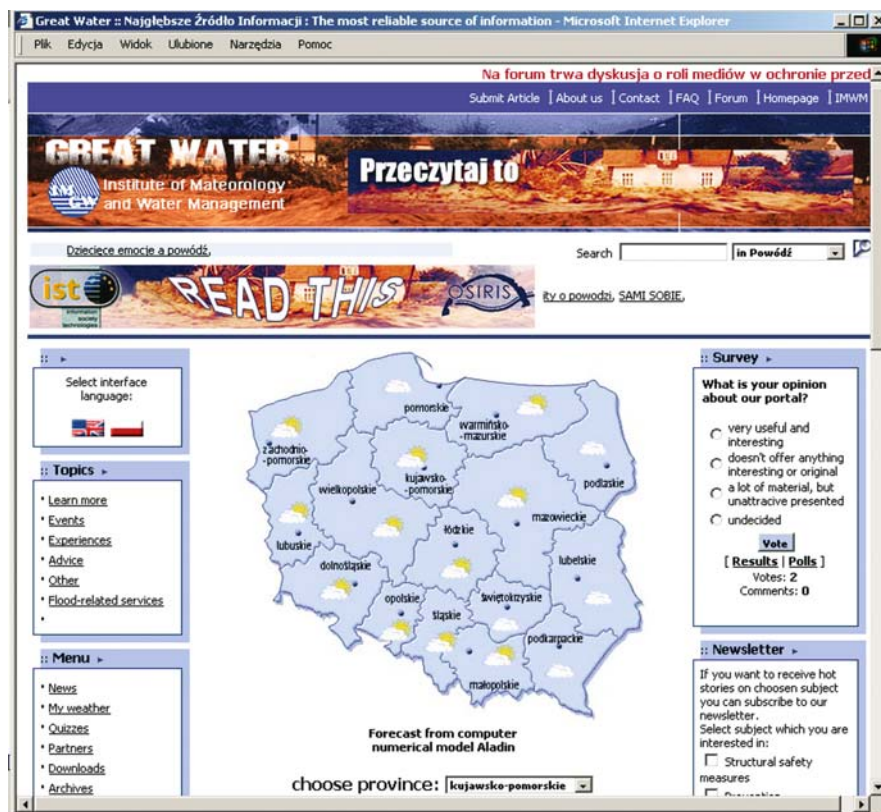


Figure 4. Interface of the Great Water (Kłodzko demonstrator K1)

3.4.3.1. *K2 – local-level decision-making aid tool* The demonstrator K2 at Kłodzko site addresses hydrological information services on local and nation-wide level. Information is assembled in a data base on which a forecast model is applied. Depending on occurrence of overstepping threshold levels, persons are automatically warned by corresponding communication services. For decision makers, information about possible risk and risk prone values are given.

The Project's objective for the K2 application is to execute and implement a prototype for tools to aid county crisis intervention structures – to permit execution of the following tasks:

- 'awakening' of crisis intervention structures in a potential flood risk situation
- aid to decision-makers in analysing available information and taking uncertainty of information into account in the decision-making process
- formulation and dissemination of messages and warnings to crisis intervention forces.

The information content is described in several categories of information, in which the content itself is classified by type (Figure 5).

3.4.3.2. *K2A – Mass telephone notification system* Mass telephone notification system is the prototype solution of the system of notification and warning of inhabitants and services against the flood threat. A commercially available system was procured to fulfil this function. The basic tasks of this system are

- efficient notification of teams responsible for the crisis management and activities during the crisis
- notification and warning of inhabitants against the existing threat
- rendering of the sources of information about the flood threat and suggested activities accessible to the inhabitants.

3.4.4. *Demonstrator Loire InfEau (L1): 'Provision of a User-Friendly Information on Hydrological Situation'*

The goal is to convey to different potential users information on the hydrological situation (observed and forecasted magnitude of a river flow with a lead time varying from few hours to two days) in such a way that it can be interrogated and processed by an user's system according to its needs, whether user is a local authority executive, a firm manager, a farmer or a citizen (Figure 6).

A local authority may automatically forward this information in an adapted form to different displaying systems under its responsibility. Or, any user can customize the system, so that it gets an appropriate information in due time.

Compliant with these objectives was implementation of a server dedicated to two services:

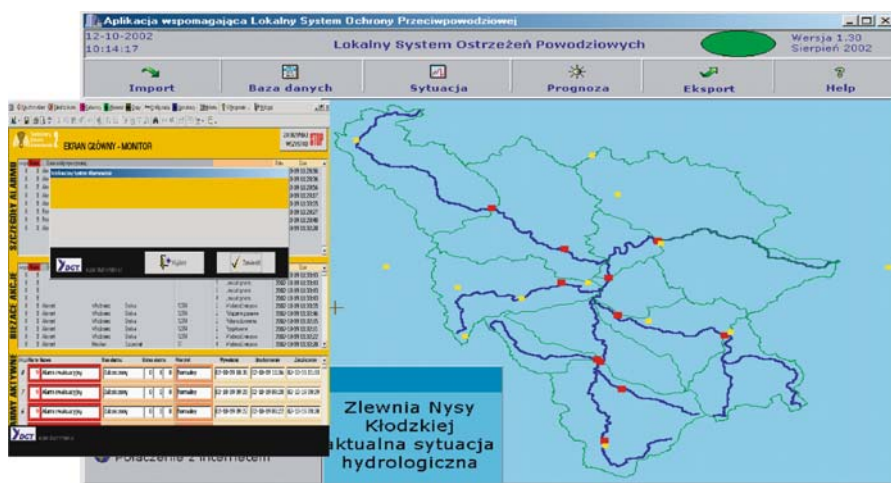


Figure 5. Interface of the Kłodzko demonstrator K2

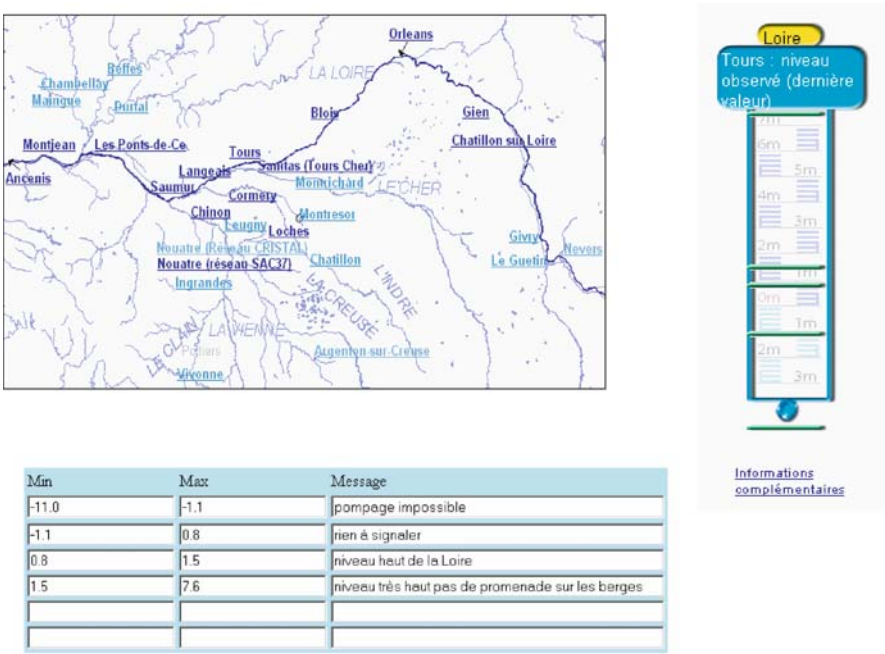


Figure 6. Interface of the Loire InfEau (Loire demonstrator L1)

- Dissemination of information (observation/forecast) on the basis of a support system allowing reuse and external system interrogation (Internet oriented data base);
- Definition and experimental implementation of some of such external systems e.g. displaying of customized web page (possibility to print a local bulletin) and displaying the information on a given variable.

Information is disseminated through three parallel channels: Internet, automatic answering machine and WAP (Wireless Application Protocol) mobile phone. Users can customize the system through profiles, so that a warning message is issued as soon as a user-defined threshold water level is exceeded.

3.4.5. *Demonstrator Loire 2 (L2): ‘Tailoring Forecast Information for Local Diagnosis and Decision Support’*

The demonstrator Loire2 (L2) aims at tailoring forecast information for local diagnosis and decision support (http://www.ist-osiris.org/extern/mockup/index_l2.html).

The high water situations and intervention plan measures are presented graphically (Figure 7).

The service consists in translating the basin-wide forecast and scenarios in local ones to facilitate the tasks of anticipating, taking decisions and providing an

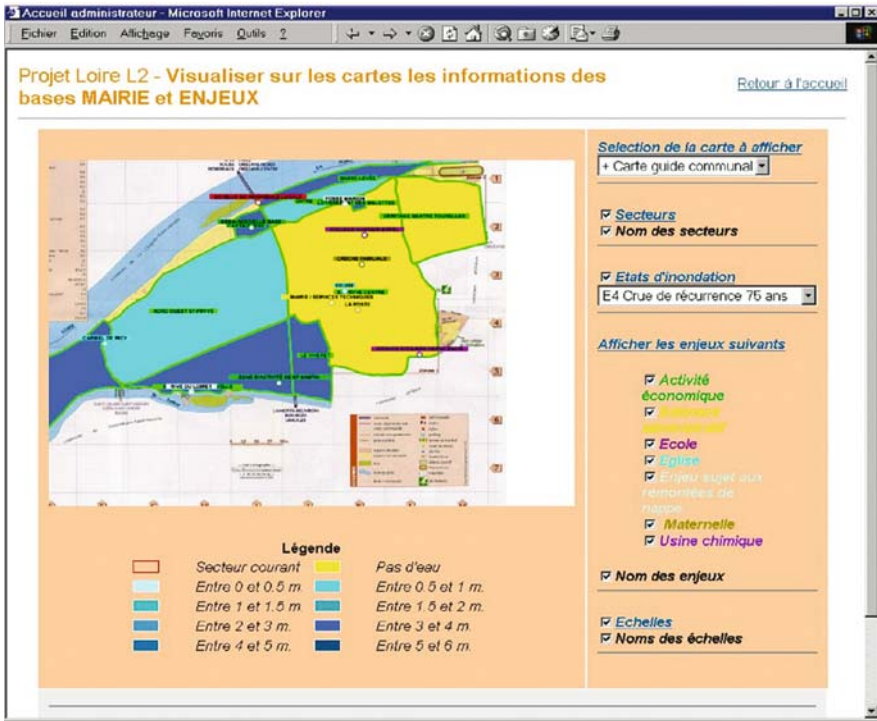


Figure 7. Interface of the Loire2 demonstrator

efficient emergency response and therefore protecting more efficiently the persons and properties.

L2 at Loire site is closely related to the L1 demonstrator. It extends information content from locations to the areas. Areas may be selected, and the level of inundation at different high water situations is presented in two-dimensional maps.

The demonstrator moreover covers graphical presentation of intervention plan measures of different stakeholders. Selection functionality is provided. The objective of the demonstrator is to provide local stakeholders, directly concerned by the flood in the field at a local community level, with an intuitive system that enables them to forecast during flood situation:

- the extension of the inundation area;
 - the consequences on local stakes;
 - to make decision for the application of pre-formatted ad-hoc actions/rescue plans.
- Basically, the tool is dedicated to non-specialist users whose main characteristics are to be in the field and to deal with decision making to prevent the consequences of flood. The main family of users could be

- local authorities (mayor, technical department, rescue or police department etc.) who will be allowed to use directly the system and communicate some of the results,
- economical and social stakeholders (factory, stock breeding, farmers, hospital etc.),
- citizen who could have direct or indirect access to the system (receiving targeted messages).

The scope of the tool covers a local community (village and city) or equivalent ('Collectivité Locale' in France), and all the potential direct or indirect stakes located in this area because of the flood impact on the local environment (Morel and Taliercio, 2003).

4. POTENTIAL SERVICES FOR FLOOD RISK MANAGEMENT

OSIRIS brings a valuable experience as far as setting up of appropriate services for information dissemination to various groups of stakeholders is concerned.

4.1. Information Dissemination Services

The goal of the Loire InfEau (Loire 1) demonstrator is to convey to different potential users information on the hydrological situation in such a way that it can be interrogated and processed by this user's system according to his needs, whether this user is a local authority executive, a firm manager, a farmer or a citizen (Figure 8). By hydrological situation, it is meant as an observed and forecasted water level with a lead time varying from few hours to two days. In this respect, Loire 1 solution aims at fulfilling the user requirements for an information available at any time, frequently updated and quickly accessed for, adaptable to all specific situations.

This hydrological information can be provided by river sensors and processed by river basin authorities, such as flood forecast centres etc. The meteorological office can be plugged in the same manner, however it was not the case in OSIRIS experimentation.

The server developed is dedicated to two services:

- Dissemination of information (observed/forecast) on the basis of a support system allowing reuse and external system interrogation (Internet oriented data base);
- Definition and experimental implementation of such external systems, for example:
 - a system displaying customized web pages (user-oriented messages);
 - a system displaying the information on a mobile device such as a mobile phone (synthetic voice for voice-oriented communication and WAP technology for Internet connection with a mobile phone).

Loire 1 basic services can fulfil a large panel of needs, they can be used for different purposes and at different scale and responsibility level. For public local authorities in particular, the possibility that inhabitants organize a parallel information path

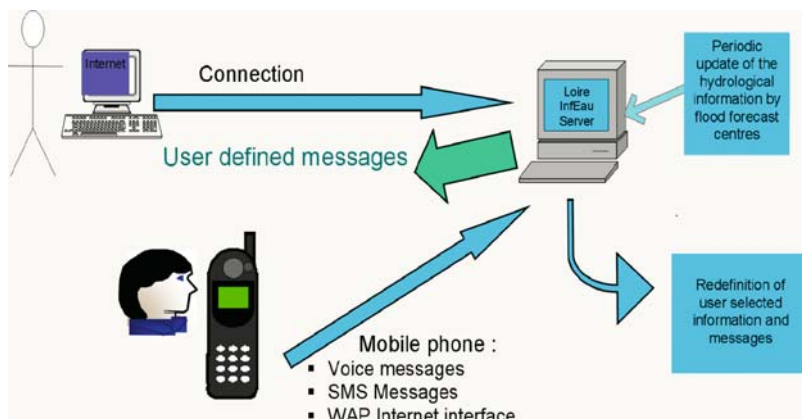


Figure 8. Principle of L1 demonstrator services

with self-defined thresholds and messages is potentially dangerous, because the messages are not under local control. That kind of fear should hopefully disappear with a longer use, in particular during flood crisis periods. A by-product of such a tool may be to increase progressively inhabitant river knowledge, enhance their feeling of responsibility and strengthen confidence between riparians and authorities on flood matters.

Loire InfEau service can be both the support and the product of these innovations provided it is promoted by a strong political will. As previously mentioned, the involvement of local authorities through the *Etablissement Public Loire*, the good collaboration with the State departments are in this respect strong assets (Blancher et al., 2003)

4.2. Services Related to Education

These services can be classified on the basis of administrative level:

County and municipal – creation of local education and information policy plans in collaboration with local entities (schools, NGOs and mass media), activism in realization of these plans, creation of information centers (e.g. using the Internet) and financing and preparation of local information publications.

Voivodship (regional level) – carrying out information policy in regional media, preparation of educational materials for schools and propagation of these materials in municipalities and counties, organization of training programs for local government crisis intervention centres, financing of model solutions in the area of education and preparation of local handbooks.

Center (national level) – preparation of a system of aid (financial and otherwise) for development of education in the area of natural catastrophe protection, creation of guidelines in this area, financing of necessary research in this area and preparation of basic educational and informational materials.

There is a common feeling that there is also a need for an international platform for exchange of knowledge and experiences in this area.

5. VALIDATION PROCESS

The validation of the demonstrators was carried on as part of the OSIRIS project activities. It consisted in confirmation (or information) that the prepared demonstrators do indeed reflect the needs and expectations of users, as articulated during the design phase. In the effect of this appraisal, the content of the individual tools was revised, necessary corrections in the software were identified as well as corrections in the user interface, suggested by the persons tested.

Tests of the usefulness and suitability of the demonstrators being built in the project were conducted with many appraisal groups associated with flood damage mitigation, as well as with inhabitants at risk for flooding. This latter group, as well as local- and county-level crisis managers, was the most frequently used appraisal group. Practically, all partners responsible for building and testing of demonstrators conducted appraisals with these groups.

For the two demonstrators being built in France, test participants also included representatives of: technical municipal and department services, elected representatives and local government institutions (EP Loire) or institutions responsible for flood safety (DIREN). In the case of the K1 demonstrator, tests were conducted with groups responsible for education (teachers) or information dissemination (journalists).

In analyses associated with appraisal of the demonstrators, many different methods of studying user opinions were used. Most often utilized were surveys, focus groups and telephone interviews. The table below contains information about what methods were used to appraise the individual demonstrators.

The validation study shows that the appraisal groups gave generally positive ratings to the demonstrators built as part of the project. It is, however, worth asking the more detailed question of whether the priorities established by the partners during the project were fulfilled, and if so, in what degree.

The fulfillment of the aforementioned priorities was done using simple method consisting in comparison with the percentage of positive and negative ratings obtained by the demonstrators from the viewpoint of the individual strategic objectives of the OSIRIS policy.

The best results were achieved in fulfillment of basic needs in the area of information access and dissemination, improvement of knowledge and awareness, collaboration and sharing of information.

The negative ratings have several causes. The most of negative ratings were obtained in the area of 'Facilitating ACCESS to information and communications technologies', which results from the fact that only two demonstrators were associated with that high-priority direction. The negative ratings for one of them – L1 – resulted from a lack of sufficient time to carry out the demonstration process – in this case very difficult and labour-intensive, because it concerned

private individuals. The process of expanding the features offered in the L1 demonstrator should be continued after the project is completed.

6. CONCLUDING REMARKS – TOWARDS FURTHER DEPLOYMENT OF THE OSIRIS RESULTS – CHALLENGES FOR THE FUTURE

The main inspiration for proposing the research programme defined in the OSIRIS Project was the catastrophic flood of the Oder/Odra river. Only in Poland during the flood, 54 persons lost their lives, about 500,000 hectares were inundated, as well as over 12,000 businesses and institutions estimated that the flood of July 1997 caused losses on the order 3.5 billion US \$.

In subsequent years, more floods occurred in Poland, albeit of lesser extent, but equally tragic in their effects. In 1998, a flood in the Klodzko Valley resulted in 9 mortalities. In 2001, in the Vistula basin, 18 persons died. It was necessary to evacuate about 20,000 persons, and losses reached 600 million US \$.

Last year flood of Elbe river (14–18 August 2003) has caused 25 fatalities in Czech Republic and Germany and flash flood of Gardon river in France (13 September 2002) resulted in 23 victims and 12 disappeared persons.

Although OSIRIS did not prevent from floods nor proposed miracle solutions, the experience acquired during the project should be considered as the most important asset for designing complementary programmes for strengthening flood protection including tools development and implementation of comprehensive educational strategies and actions.

The major strength of the Project was (and still is) the credibility of its partnership. In particular, the presence of partners representing either public administration or local self-governmental bodies directly involved in the process of the acquisition, processing and dissemination of the information on flood risks allowed organization of all phases of the OSIRIS in direct connection with other stakeholders in three pilot basins.

At the same time, a strong determination of the partners in charge of the demonstrator applications is to continue (at least for next couple of months) the experimentation phase started within the project and to exploit the OSIRIS results in the form of industrialized tools, with the wider deployment in other basins. It delivers an important dose of optimism to all the OSIRIS participants.

The recent production of the Theatre du Soleil untitled ‘Flood drummers’ (‘Tambours sur la Digue’) tells a story of a regent and the tragedy of his kingdom. The piece begins when the river that divides the country in two parts is about to flood the land because of heavy rainfalls. The only way to save the kingdom is to sacrifice either the northern or the southern part, by tearing down a dike and saving the other half. The lack of communication between rulers and riparian population leads to a crisis, which puts the industrialized, urban North against the culturally blossoming villages of the South. Conspiracies within the royal society develop to bloody fights, almost like we know them from Shakespearean tragedies.

The dramatic circumstances of the past catastrophic floods that occurred just in Europe during OSIRIS Project life cycle (Elbe, Gardon) as well as the risks concerning future events give us some modest hope that the multidisciplinary approach, methodologies and prototypes of tools the OSIRIS Project developed will contribute to finding appropriate solutions to future flood crisis management.

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CHAPTER 4

EVOLVING CONCEPTS IN FLOOD RISK MANAGEMENT: SEARCHING FOR A COMMON LANGUAGE

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Abstract: Flood management is increasingly discussed as a risk management process, encapsulating as this does, terms such as ‘resilience’, ‘vulnerability’, ‘hazard and ‘uncertainty’. The question is, is there a common consensus about what flood risk management means?

The discussion of flood risk management is often confused by the use of language, which in turn obscures meaning. It is not always clear whether the concepts of ‘vulnerability’ and ‘resilience’ are new concepts, new labels applied to existing concepts or whether they are being consistently applied. There is consequently a risk that we are either talking about entirely different things using the same labels, or talking about the same things using different labels

Diluting this ambiguity is the aim of the paper. After all, if we are to advance flood risk management in practice then we need a coherent set of concepts. This paper explores the range of concepts currently employed in the flood risk management literature in an attempt to provide a consistent and unambiguous language to improve communication and knowledge dissemination. To do so, requires an examination of a range of important concepts including, ‘resilience’, ‘resistance’, ‘vulnerability’ and ‘uncertainty’. In this paper these concepts are defined and discussed by adopting a dynamic systems approach and recognizing that both the climate and flood risk management systems are constantly changing and developing

Keywords: flood risk management, resilience, vulnerability, risk, uncertainty, dynamic systems

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1. INTRODUCTION

Flood risk management (FRM) is the latest approach to emerge in the flood hazard policy domain. Where previously, managing floods was discussed in terms of land drainage and flood defence, the trend towards managing the 'flood risk' is being increasingly popularised. This has resulted in numerous documents, which describe this new, or changed, vision together with the necessary policies, problems and characteristics. Terms such as 'room for rivers', 'holding the line', 'living with floods' and 'working with nature' are frequently used (MAFF, 1995; Min. VROM & V&W, 1997; Min. V&W, 1998; ICE, 2001). As the flood hazard orthodoxy changes, so too does the meaning, relevance and importance of concepts such as 'resilience', 'vulnerability', 'uncertainty' and 'susceptibility'. The intention in this paper is to examine a number of key concepts in the prevailing attitude towards FRM in order to provide an important first step in the search for a common language through which to communicate.

In searching for a common language we may simultaneously have too many words, so that different words are being used for the same concepts, and too few words, so that the same word is defined and applied in different ways. This lack of consistency in the use of concepts has resulted in confusion over what is new about the policies and approaches that use these concepts, to what degree they are consistent, and where they differ from existing ideas and policies.

The paper gives an overview of the meanings of different concepts and seeks to clarify these concepts and their relationships in order to create clarity. First, the paper discusses what is meant by FRM, the practical implications of this delineation, and why it is an important concept for definition. The authors then go on to critically evaluate the key concepts which characterise FRM, namely 'resilience', 'resistance', 'vulnerability', 'hazard', 'susceptibility' and 'uncertainty'. In discussing the range of meanings employed for these terms, the authors examine the relationships between each concept, evaluating the importance of this for FRM. Critically, they conclude that these terms shift the problem to one of the management of dynamic and interacting systems and away from a static concept of flood control. Although most of the ideas are generally applicable, the paper focuses on lowland river floods and studies them from a catchment perspective.

2. FLOOD RISK MANAGEMENT: AN INTEGRATED APPROACH TO COPING WITH FLOODS

Flood risk management has to be considered within the contexts of both sustainable water management and sustainable development. The principles of sustainable water management were set out in the Dublin declaration (ACC/ISGWR, 1992) and have subsequently been expanded in the form of Integrated Water Resource Management (GWB, 2000). Central to IWRM is the need to manage all aspects of water and water use in a systemic manner and also to manage both water and land across the catchment as a whole. From the wider sustainable development perspective, IWRM

has to be integrated with other aspects of development, including national energy policy, but also with rural-urban development (Green, 2003a).

By considering FRM in a broader context, we move away from the traditional focus of *defending against* floods to a focus on *managing flood risks*. The term flood risk is used in a number of ways dependent on whether the user is referring solely to the probability of the flood occurrence, the impact of the flood or, as is more generally argued, as a combination of the probability and the potential consequences. The meaning of the term 'flood risk' depends on the focus of the decision-maker in question, the language adopted and the tools used. Flood risk is, for example, interpreted differently by householders in floodplains than it is by national-level decision-makers responsible for weighing the costs and benefits of national resource investment (Green et al., 1991; Hall et al., 2003). In this paper, flood risk is defined as the expected annual damage and depends thus on both the flood probabilities and the flood impacts. FRM is defined as the combination of all activities that aim at maintaining or improving the ability of a region to cope with peak discharges or extreme rainfall events.

To manage flood risks, decision-makers have to manage disturbances in both the short- and long-term. In the short term, extreme peak discharges and rainfall events resulting from climate variability have to be coped with, while these perturbations in the long-term are effected by continuous trends, cyclical changes and unexplained variance in the climate. Since these long-term changes influence flood probabilities in the future, they have to be taken into account in FRM strategies of today, whilst recognising the uncertainties that they add to the decision-making context. It is important to recognise that apparent pattern-less variation is not necessarily a result of a 'random' process. Rather it is arguably a result of our lack of understanding of the process of change in a dynamic system. FRM should not only concerned with managing extreme rainfall or discharge events but also about influencing the interaction between these events with the river and the flood-prone region. After all, FRM is not an aim in itself but rather a means to enable a region to function 'normally' when disturbed by extreme events. Thus, next to changes in the flood probabilities and rainfall events, FRM must consider changes in the physical and socio-economic characteristics of the flood-prone area and in its long-term strategies. Changes both in the potential consequences of floods and in the preference of measures as a result of, amongst others, changes in norms, values, population increases and land use are significant for the choice of a FRM strategy.

To manage flood risk, and its associated uncertainties, requires a management system which improves not only a region's ability to cope with extreme rainfall events, or peak discharges in annual variability, but also with the change in the frequency and severity of these perturbations over time. This is only possible if a systems perspective is applied to the management of the flood risk. In this sense, FRM must be synonymous with a systems approach: where the system consists geographically of the river system, the catchment and the flood prone area and conceptually of two sub-systems based on the physical and socio-economic

characteristics of this area. Focussing on lowland river floods, for example, this whole system can be sub-divided into the lowland and upland system which contain both a physical subsystem (e.g. geomorphological, ecological, hydrological and structural characteristics) and a socio-economic subsystem (e.g. household, companies, trade, institutions, economy and population characteristics) (Figure 1). The total system has to cope with many disturbances, but in the case of FRM we focus mainly on extreme rainfall events that may disturb the upper catchment system and act as a disturbance on the lowland system. The purpose of FRM is to create a balance between, and thus be able to manage, the socio-economic and physical characteristics of the system and the rainfall or peak discharges entering the system.

This system is *dynamic*. It is constantly changing state due to the changing relationships between the various sub-system characteristics, and to disturbances in the form of extreme rainfall events or longer-term changes such as a changing climate or a changing population. In systems theory (Di Stefano et al., 1967) and its various offshoots, including chaos theory (Gleick, 1987), systems are taken to have different stability domains or domains of attraction. Provided that the state of the system remains in a given stability domain after a disturbance then it will tend to return to its initial state. But, given a sufficient disturbance, it will shift into a different stability domain; a discontinuous change occurs. In the case of the socio-economic subsystem, we generally want to avoid rapid and irreversible changes of state. The dynamic systems approach must form the essence of FRM. This provides the framework within which a range of concepts such as resilience, susceptibility, vulnerability, hazard and uncertainty can be defined. These concepts are very important in the FRM literature and are discussed below.

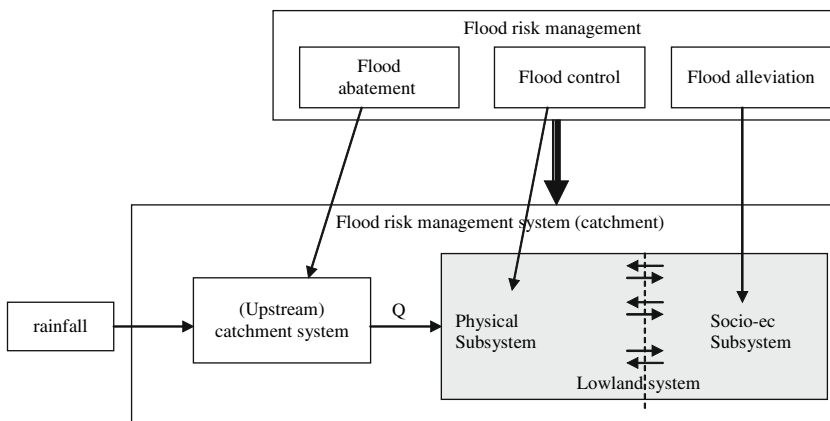


Figure 1. Flood risk management from a systems perspective

3. DEFINING RESILIENCE FOR FRM

'Resilience' is a word that is increasingly used in FRM and elsewhere (McFadden, 2001; Vis et al., 2003; De Bruijn, 2004). As a concept, resilience has been taken from the original use in material science, so that the traditional definition is '*returning to the original point, springing back, recoiling*' (Shorter Oxford English Dictionary, 3rd edition). The problem with this definition in FRM is that resilient materials are necessarily easily deformed by a load. In the case of flood management, a rapid and complete recovery is important but without the system being easily deformed. Generally, we want some elements of the overall system to be resistant; not to be easily deformed by a transient load.

Another definition of resilience has developed in psychology and psychiatry (Waller, 2001). Here, resilience is defined as '*positive adaptation in response to adversity*' and includes as part of that adaptation both changing the stressor and learning to respond more effectively. Resilience is thereby defined as the interaction between the individual and their environment, rather than a property of the individual. This idea may bring two important ideas to FRM, that resilience is both transitional and dynamic. However, as a transaction between the individual and their environment, the context is important: a single perturbation (e.g. a peak discharge) is only part of the wider pattern of disturbances to which the system must respond.

A further definition of resilience, taken from the coastal zone management literature, refers to *the ability of a system to preserve its functional capacity under forcing* (McFadden, 2001). This may be related to the self-organising nature of the system which makes it recover; however it may also represent the ability of a system to recover from a perturbation where it is unable to come back to its original form without spatial change. The structure of a resilient system may change relatively dramatically: the important point is that the functions provided by the system can be maintained under external forcing (McFadden, 2001). In this definition McFadden highlights the process-based nature of both physical and socio-economic systems, where change is the norm but where dynamic equilibrium may be maintained. For FRM, the definition re-enforces the need for resilience to be conceptualised as a dynamic attribute of flood risk systems.

Examining the current use of the resilience concept in FRM, we find that the term is essentially taken from ecological science. In ecosystem theories two definitions of resilience can be found (De Bruijn, 2004). In the first instance, resilience is defined as *the ability of a system to maintain its most important processes and characteristics when subjected to disturbances* (Holling, 1973). Holling introduced the concept of resilience next to common ideas on stability to emphasize that systems do not have a static equilibrium state to which they return, but that instead systems develop and change but maintain their most important characteristics. A system in which sudden changes or collapses can occur, or a system that changes dramatically by small disturbances is not considered resilient (Collet, 1997). This definition has been used to describe the dynamics of a variety of ecosystems, including freshwater lakes (Carpenter & Cottingham, 1997) and forests (Ludwig et al., 1997).

This definition has also been used in the study of the resilience of socio-economic systems (Adger, 2000) and coastal zone management.

The second definition of resilience in ecology expresses the *ability of a system to return to an earlier equilibrium or development pattern after a disturbance*. This concept originates from stability theories and is valid for systems that operate at, or near, a global equilibrium (May, 1974; O'Neill, 1976; Pimm, 1984; Tørgensen, 1992; Begon et al., 1996; Pérez-España & Arreguín-Sánchez, 1999). According to this definition, resilience is equal to the return time of a system (O'Neill, 1976; Kwa & Ringelberg, 1984; Pérez-España & Arreguín-Sánchez, 1999) or as a combination of the amplitude of the reaction on the disturbance and the time needed to return to the equilibrium (O'Neill, 1976). It incorporates the ability of the system to cope with extreme events only after the system has reacted to the external forcing.

Recent work examining resilience in FRM of lowland rivers has been conducted by De Bruijn (De Bruijn, 2003; De Bruijn, 2004). De Bruijn (2003) has defined the resilience concept as *the ease with which the system, consisting of the socio-economic and physical aspects of the flood-prone area and the river, recovers from floods*. The concept of resistance is used to define the ability of a system to prevent floods. The resilience and resistance of a system thus reflect the system's reaction to flood waves. In the De Bruijn approach resilience is a function of three parameters that together describe the reaction of a system to flood waves coming from the upper river (the approach focuses on lowland rivers): the amplitude, graduality and the recovery rate. Amplitude is defined as the magnitude of the reaction to extreme rainfall events. The graduality of the reaction describes the increase of the reaction with increasingly severe disturbances and the recovery rate describes how fast a system will overcome the reaction to the disturbance (Figure 2). De Bruijn argues that the three cannot be merged to one indicator or added without the loss of significant information (De Bruijn, 2004b).

Figure 2 illustrates this conceptualisation; small disturbances do not change the system state at all, the system is resistant to them. Somewhat larger disturbances do change the state of the system but when the disturbance is passed, the system recovers to its initial state. Given a sufficiently large disturbance, the system may not recover any more but instead it will end up in a completely different state than where it started. For example, in the Elisabeth flood in 1421 suddenly a large area in the Netherlands became inundated. After the storm a large area stayed wet. What was an agricultural area with many villages is nowadays covered by a large wetland called 'De Biesbosch'.

Apart from the definition of the term there is also disparity in the contextual framework of resilience. Some authors only include natural resilience, whilst others focus solely on adaptation in the socio-economic environment. Finally, some authors include not only the ability to recover from the impacts of shocks or short-duration events, but also the capacity to adapt to long-term changes as an element of resilience (Klein et al., 1998). By contrast, others clearly distinguish between resilience for shocks (flood waves or rainfall events) and adaptability for climate change, because

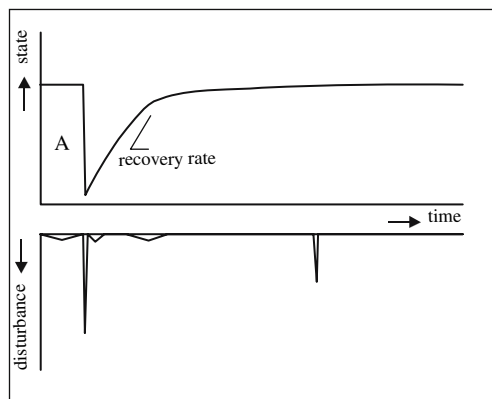


Figure 2. The system in the figure has resistance to cope with small disturbances; therefore, it does not react on small disturbances. In response to larger disturbances, the system behaves resilient. The degree of resilience can be characterised by the reaction amplitude (A) and the recovery rate

a continuously applied disturbance will eventually drive any system out of its stability domain, regardless of the size of the domain. In this paper resilience is used to express the system's ability to recover from the reaction on temporary disturbances (peak discharges, extreme rainfall events), while adaptability is used to express a system's ability to cope with changes and trends (climate change, population increase). The critical point emerging from this analysis is that resilience is a dynamic process which includes the ability of the system to maintain its pattern of behaviour given perturbation. This idea is central to the effective use of the concept for FRM.

4. NATURAL HAZARDS AND VULNERABILITY

Vulnerability is another term that has been used in many different ways (Table II), although as a concept it has often attracted less discussion than that of resilience. According to the Oxford Dictionary, vulnerability is defined as the *liability to be exposed to disaster*. The vulnerability concept has been considered as a systems property, a property of buildings or structures or land use types or of individuals or social groups.

In quantitative terms vulnerability is associated with the extent of harm or damage that results from an event. In engineering science the concept is mostly linked to physical objects i.e. houses, vehicles etc.. For FRM, vulnerability would thus be defined as the potential physical damage given a certain discharge and dike breach. Another dominant use of the vulnerability concept is in the context of social science (e.g. [Blaikie et al., 1994](#)), where vulnerability is defined as the degree to which life and livelihood are affected by a disturbance. In this instance, features such as information, cultural knowledge, social networks, legal rights as well as physical resources are important determinants of vulnerability within a region.

Table 1. Vulnerability: a range of definitions

A measure of the potential for loss of the physical, economic and social value of a given site. Vulnerability is a product of the interaction of susceptibility and resilience within the system. (McFadden, 2001)
The potential for attributes of a system to respond adversely to the occurrence of hazardous events (Yamada et al., 1993)
The potential of an ecosystem to modulate its response to stressors over time and space, where that potential is determined by characteristics of an ecosystem that include many levels of organisation. It is an estimate of the inability of an ecosystem to tolerate stressors over time and space (Williams and Kapuska, 2000)
A function of a system's ability to cope with stress and shock (Nicholls and Klein, 2000)
The interaction of the threat to the system and the capacity of that system to successfully adapt to or cope with that threat (Green et al., 2000)
The propensity of an endangered element due to any kind of natural hazard to suffer different degrees of loss or amount of damage depending on its particular social, economic, cultural and political weaknesses (Alcantara-Ayala, 2000)

In a review of the vulnerability concept, (McFadden, 2001) highlights the importance of an interdisciplinary approach. This is an important step towards developing a common language FRM. Vulnerability must incorporate all aspects of the system under risk from flooding. The nature of the hazard identifies those system characteristics that are most important in a vulnerability analysis. The height above sea level, for example, is a critical characteristic that defines the vulnerability of the system given high-water levels in a flooding event. However, if the disturbance is not natural (world market crises or AIDS), population and structural characteristics are more important in quantifying the vulnerability of the system.

Concern with vulnerability has varied over time, with our attention shifting from one set of concepts to another. In particular the vulnerability literature has focussed on the coping capacity of the system. However, there has to be a susceptibility to the specific form of forcing before the system is vulnerable to that disturbance. Hence, susceptibility is an important component of vulnerability analysis. Susceptibility is not equal to the exposure of the hazard. In the example of flood risk systems, houses on poles or floating houses may be considered exposed to floods, while they are not necessarily susceptible. Vulnerability must, therefore, be defined as a combination of susceptibility and recovery or adaptation. In turn, susceptibility is defined as the degree to which a system would be affected by a disturbance or change in its environment. The important point to note is that the vulnerability of a system is time varying. FRM must recognise vulnerability as dynamic and process-driven.

5. THE ROLE OF UNCERTAINTY IN FLOOD RISK MANAGEMENT

Uncertainty has been defined in a variety of ways (Table 2). The classic definition of uncertainty given by (Knight (1921)), and followed by (Keynes (1937)), is simply as that which is unknown and perhaps unknowable. The problem with the

Table 2. Uncertainty: a range of definitions

Uncertainty must be taken in a sense radically distinct from the familiar notion of risk, from which it has never been properly separated. It will appear that a measurable uncertainty, or 'risk' proper... is so far different from an unmeasurable one that it is not in effect an uncertainty at all (Knight, 1921)
About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know (Keynes, 1973)
The state in which the number of possible outcomes exceed the number of actual outcomes and when no probabilities can be attached to each possible outcome (Bannock et al., 1987)
State of maximum entropy: where all choices or all outcomes are equally likely (Green et al., 2000)
An expression of the degree to which a value (e.g. the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable (IPCC, 2001)
In situations of uncertainty, the fluctuations of a variable are such that they cannot be described by a probability calculus. Thus risk and uncertainty are best thought of as representing a spectrum... ranging from perfect knowledge... to no knowledge of the likelihood of possible outcomes at the other (ADB, 2002)
A characteristic of a system or decision where the probabilities that certain state or outcomes have occurred or may occur is not precisely known. A concept that reflects a lack of confidence about something, including forecasts. Decision-makers may have more or less certain knowledge of a risk (Willows & Connell, 2003)

Knightian definition is that it does not appear to provide any guidance as to how uncertainty should be incorporated in decisions.

More recently there has been a tendency to define uncertainty instead as a form of risk; here for example the definition by the IPCC (2000) is illustrative. Likewise, a related approach has been to avoid defining uncertainty at all but instead to treat it as if it is risk (e.g. Belli et al., 1997). From this perspective, taking account of risk in decisions is relatively straightforward and there is a range of techniques which can be adopted when the choice involves risks (ADB, 2002). Thus, uncertainties are incorporated by quantifying them with the help of Monte Carlo Analysis and optimisation techniques by using probability functions for the relevant variables (Green, 2003). In our opinion this last approach is not comprehensive. Uncertainty may result from an imprecise knowledge of risk, i.e. when probabilities and magnitude of either hazards or their consequences are uncertain. Even when they are certain, there is still uncertainty, since it is still unknown if and when they will occur (Willows & Connell, 2003). However, there are many more types of uncertainties that are not related to risks.

More insight in the effect of uncertainties on flood risk management can be gained by studying the origin of uncertainties and different types of uncertainties. Sources of uncertainty can be lack of knowledge and/or natural variability (Van Asselt & Rotmans, 2000) and they can present themselves as technical or statistical uncertainties, methodological uncertainties and fundamental uncertainties. *Technical*

or *statistical* uncertainties are uncertainties that surround a variable when its state at any one point is unknown, but the probability distribution that characterizes that variable is known (Hilborn, 1987). An example is the uncertainty on whether you may win a lottery. *Methodological uncertainties* occur when the relationship between parameters or the processes are not understood. These uncertainties are often neglected. Most modellers assume that their models are perfect, although obviously models are just a simplified representation of reality. *Fundamental uncertainties* arise on subjects where we cannot know anything about because they never occurred before.

Whether uncertainties are important depends on the influence they have on decisions. *Decision uncertainty* is *doubt* on what choice to make (Green, 2003). It may arise from lack of knowledge on the options available, the consequences of the options, the future state of the system, or on knowledge on or agreement on the decision criteria (Green, 2003). For decision making it is only useful to reduce uncertainties if this may change the ranking of alternative options. If the ranking of alternatives is *certain*, although many aspects are uncertain, still a decision can be taken (Green, 2003).

One of the most important uncertainties in flood risk management is variability in nature. If flood waves would always occur on the same time and with the same magnitude, they would be easier to manage better. However, nobody knows if, when and how frequently certain discharge waves will occur. Other aspects that are uncertain to some degree are: the division of water over different branches, stage-discharge relationships for extreme discharges, dike stability, flood impacts, behaviour of the inhabitants, effects of measures, etc. These uncertainties are important for the current system. Considering the future, uncertainties as to how the system will behave in the future also have to be added. Society will develop which will change land use patterns, norms and values and probably the climate and the river system will change also.

It has become clear that uncertainties cannot be avoided or solved. However, decisions have to be taken. Important questions for flood risk managers are: "What decisions should be taken, given all uncertainties?" "What might go wrong and under what circumstances may this go wrong?" "What are the consequences and how can these consequences be attenuated?"

Since some systems can deal better with the consequences of uncertainties, flood risk managers might try to manage their system in such a way that these unexpected disturbances and changes can be coped with more successfully. Systems that are able to cope with all kind of circumstances and changes can be called *robust*. Not only the system can be robust but also a flood risk management strategy. A flood risk management strategy is robust when it remains a good strategy in a large range of circumstances. These circumstances are for example changed economic interests, norms and values. The robustness of a system is a function of its resilience, resistance, susceptibility to changes and adaptability.

Uncertainties, such as the fact that we do not know when extreme flood waves will occur and how extreme they will be, is better reflected in resilience strategies

than in resistance strategies. In resistance strategies uncertainties can be incorporated by over dimensioning the dikes and other structures. However, still it is uncertain if and when floods will occur. In resistant flood risk management systems, the inhabitants are mostly not aware of the flood risk. They have a false sense of security, which may result in a rapid economic development in flood-prone areas, and in disasters when floods do happen. Since small floods or a fast recovery from flood impacts are not very likely in resistant systems, the possibility to learn from experiences with floods and to adapt the system in order to cope better with floods is absent. In contrast, a resilience strategy is mostly chosen explicitly to account with uncertainty. Because floods cannot be prevented, measures to limit the impacts and enhance recovery are required. Since resilience strategies focus on the whole discharge regime and not only a certain design discharge or threshold, the possibility of extreme discharges and floods is evident. Resilient systems recover quickly from flood impacts. Therefore, there is an opportunity to learn from floods and to improve the way floods are coped.

6. RELATIONSHIPS BETWEEN CONCEPTS

The importance of the concepts discussed above is that they indicate that systems are dynamic and inherently uncertain. The concern in FRM is how to respond to changing perturbations over time in a way that enables the socio-economic system to achieve the long-term, sustainable, path of development. Instead of defining risk in terms of frequency distributions, the systems model defines it in terms of a signal or a time series analysis; it is the variation over time that is critical. Consequently, floods have to be understood as a process rather than a state, and 'flooding' as being simply a label applied to one extreme of the time varying pattern of flows in rivers. In turn, there is a need to abandon designing for floods of a designated probability of occurrence and instead to consider how we will manage all floods. This means that we need to consider how any element in a sub-system will fail and the consequences of that failure.

In managing the systems, we have two concerns. Firstly, we want the socio-economic system to respond to specific disturbances in particular ways, to exhibit resilience or resistance. All definitions of resilience include at least the ability of a system to cope with perturbations. Where some of the confusion arises is in part dependent on what it is that is being described as 'resilient': the natural environment, or the socio-economic system. The first is in principle self-organising in that it adapts to changes, however its capacity to be self-organising can be (and often is) limited by human activity. Geomorphological systems typically need space in which to adjust, and they, along with ecosystem, need time (McFadden, 2001). Allowing space is often a problem: that a river can respond to an extreme event by radically changing its course is not helpful in a socio-economic context. Both geomorphological systems and ecosystems also need time to recover. This is a problem if the next flood occurs before the natural system has had time to recover from the impact of a previous perturbation. Conversely, the socio-economic system

must be managed to be resilient, unless the most optimistic claims are made as to the performance of a market economy. The variability in resilience across the socio-economic and physical environment must be recognised when managing flood risk within a system. So, resilience defines the momentary capacity of a system as a whole, to respond to a regime of disturbances in a way that enables the socio-economic system to return to the long-term sustainable growth path as quickly as possible, or as near as possible to that growth path. When a system is resistant, it does not change state for any disturbance up to some magnitude of disturbance. Both these terms define the dynamic response of the system when subject to a disturbance. In broad terms, we want to select the response of the system to be resistant or resilient across a range of disturbances.

Secondly, in order to achieve the desired response, we are concerned to manipulate the characteristics of those sub-systems, and the relations between the subsystems. It is these systems characteristics, or the structure of the impacted system and the system impacting upon it, and the dynamic relationship between these systems that determine the extent to which the impacted system exhibits either resilience or resistance. It is this that may then be termed vulnerability: it varies over time and is defined by the states at any one time of the two systems as partly determined by the relationship between them. Resilience thus describes how a system recovers from a disturbance, vulnerability is the label applied to the discussion of why a system responds in a given way.

Strictly speaking, vulnerability only applies to those disturbances to which the impacted system is exposed and to which the system is susceptible; those disturbances which threaten to take the impacted system outside of its capacity to respond successfully either resiliently or with resistance. These two conditions, of system susceptibility and exposure, consequently define a hazard; a hazard is a source of disturbances to which the impacted system is susceptible and exposed. If someone says that they only have high waters, they do not have floods, they are asserting that the high waters do not threaten their capacity to cope with those floods, they are not susceptible to those water levels. Hence, in Bangladesh, one word is used to describe the annual floods to which the communities are adapted and upon which they are to some extent dependent, and another to define a catastrophic event (Paul, 1984). In short, hazards are construed.

Both the resilience and the vulnerability of a system to peak discharges change constantly due to changes within the system, partly as reactions to other disturbances that the system has to cope with and due to historic floods. Experience is likely to improve response capacity but the response capacity may have been diminished by previous disturbances. For example, the capacity of a socio-economic system to respond to, and recover from, a flood may be reduced if the socio-economic system is still recovering from a drought.

We would like to prevent disturbances of the FRM system or change the physical characteristics of the system in such a way, that disturbances are filtered out before they impinge on the socio-economic subsystem. If any disturbance is passed onto the socio-economic subsystem we want it to be both slowly changing and low

in amplitude; we do not want any rapid and large magnitude changes since they represent disasters. If flood prevention is not possible, and nowadays it is believed that it is not possible or at least not feasible, we thus want the FRM system to be resilient.

7. CONCLUSION

Words matter in the extent to which, on the one hand, they give insight into the decisions we must make and, on the other, they carry sufficient shared meaning to enable us to communicate with each other. If they provide no insight then that communication would serve no end. Part of that insight can arise through the understanding of the differences in which we interpret and understand the world, and hence the different ways in which we use words and the differences in the concepts which we are implying when we use a particular word. Discussions on the meaning of words, and the different conceptualisations of the world, are therefore intrinsically useful, especially as these discussions illuminate differences between the worldviews of different individuals or groups. At the same time, words are not neutral; we use them in order to persuade others and one strategy to do so is to re-package a preferred approach under a popular label. Consequently, differences in the use of terms arise, not because we inherently define them in different ways, but because we are trying to persuade others to adopt our point of view. To convince others, for example, that a resilient strategy for FRM necessarily involves a given package of actions.

Adopting a reflexive approach, the worldview underlying the discussion in this paper is one of interacting systems that change dynamically over time, where the purpose of decision-making is to make positive change. It is also a worldview in which uncertainty is a necessary part of the human condition. The paper argues that to be effective in FRM, concepts must they shift attention away from what has been a predominantly static and historical perspective to a systems dynamic approach. This focuses attention on change over time and on relationships between systems and subsystems. The concepts themselves for which a word is being used as a referent are often multi-faceted. Uncertainty, resilience and vulnerability are all complex concepts or constellations of concepts. What is important is that because meanings reflect worldviews, discussions of FRM must avoid sliding from one meaning of a word to another without careful consideration.

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CHAPTER 5

COMRISK – A TRANSNATIONAL PROJECT OF PUBLIC AUTHORITIES ON COASTAL RISK MANAGEMENT

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Abstract: Storm surges present a major natural hazard in the North Sea region (NSR). In this region, coastal lowlands occupy an area of about 40,000 km². More than 16 million people live here, and major economic activities take place. Without appropriate flood defence measures these lowlands may become flooded during severe storm surges. In order to achieve a sharing of knowledge and a balanced approach on coastal risk management, the North Sea Coastal Management Group decided in 2002 to initiate a transnational project: “COMRISK – common strategies to reduce the risk of storm floods in coastal lowlands”. The project is co-financed by the European Union under its INTERREG IIIB programme for the NSR. In this paper, the project is introduced as an example of international co-operation of public authorities on coastal risk management, and first results of two subprojects are presented

Keywords: coastal risk management, coastal flood defence, storm surge, coastal flooding, international co-operation

1. INTRODUCTION

Storm surges present a major natural hazard in the North Sea region (NSR). In this region, coastal lowlands occupy an area of about 40,000 km² (Figure 1). More than 16 million people live here, and major economic activities take place. Without appropriate countermeasures, these lowlands may become flooded during severe storm surges. To prevent this, national Governments spend several hundred million Euros per year on coastal defence or, rather, coastal risk management in the NSR. In future, with an accelerating sea level rise and changes in storminess

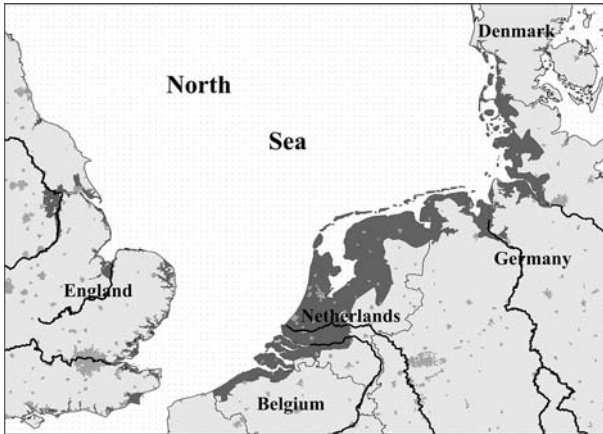


Figure 1. Coastal flood-prone areas in the North Sea region

(IPCC, 2001), the necessary budget to maintain present safety standards might increase significantly (CPSL, 2001).

Apart perhaps from Bangladesh, in no other region in the world the potential losses (lives and assets) resulting from storm surges or, rather, coastal flooding are higher. The fact that this is not so much “in the peoples mind” may result from the success of coastal risk management. The last catastrophic storm floods occurred in 1953 in the Netherlands and England, and in 1962 in Germany. In all, more than 2,400 people lost their lives. After these catastrophes, national governments undertook huge efforts to improve the safety standards, in the Netherlands by the so called “Deltawerken”. As a result, the risk of coastal flooding was significantly reduced, but still existent. For example, in Hamburg storm surge water levels of up to 0.8 m higher than in 1962 have been observed, but no major damage occurred. As a result, people feel safe in coastal lowlands, and the public awareness and perception of the risk is rather low.

In 1996, on the initiative of the Danish Kystdirektoratet, national and regional coastal risk management authorities in the Netherlands, Belgium, the UK, Germany and Denmark started an informal network, the North Sea Coastal Management Group (NSCMG). Basic idea was an improved international co-operation and co-ordination of transnational issues on coastal risk management, including the economics of beach nourishment, the improvement of public awareness and EU-regulations. Later, topics like risk strategies, climate change and research in coastal engineering, were introduced. Each year, national delegations of senior public officers and engineers meet in one of the member states to discuss common issues. From these meetings it became clear that, in order to achieve a sharing of knowledge and a balanced approach, a more comprehensive co-operation about coastal risk management throughout the NSR is expedient. On the basis of these considerations, the idea for a NSCMG project: “COMRISK – Common strategies to reduce the

risk of storm floods in coastal lowlands” was born. In the next section, the running project is described in more detail as an example of international co-operation on coastal risk management.

2. THE PROJECT

Under the Community Initiative Program INTERREG IIIB the European Union co-finances (with maximal 50%) transnational projects for specific regions, for instance the North Sea region (NSR). One of the program themes, under which projects may run, is called: “Risk management strategies for coastal areas prone to disasters and natural threats and for the North Sea”.

COMRISK is an INTERREG IIIB project that runs from July 2002 to June 2005 with a budget of 1.8 million Euros. It is a consortium of seven public coastal risk management authorities in the NSR: (1) the Coastal Defence Division of the Schleswig-Holstein State Ministry of the Interior (lead partner), (2) the Lower Saxony Water Management and Coastal Defence Agency, (3) the Coastal Authority of the Danish Ministry of Transport, (4) the Coastal Waterways Division of the Belgian Ministry of the Flemish Community, Waterways and Maritime Affairs, (5) the National Institute for Coastal and Marine Management of the Dutch Ministry of Transport, Public Works and Water Management, (6) the Road and Hydraulic Engineering Division of the Dutch Ministry of Transport, Public Works and Water Management, and (7) the Centre for Risk and Forecasting of the Environment Agency of England and Wales.

The impact that COMRISK wants to achieve is ensuring a sustainable, harmonious and balanced development in the coastal lowlands of the NSR. For this, an adequate coastal defence is a prerequisite. Hence, COMRISK aims at improved coastal flood risk management through a transfer and evaluation of knowledge and methods as well as pilot studies. The project is divided into two main parts, the umbrella project and nine subprojects. The umbrella project focuses on an exchange of experience and on the co-ordination and integration of the subprojects. The nine subprojects (five evaluation and four case studies, Figure 2) contribute to the general objectives, each having one thematic or regional focus. The five evaluation studies investigate: (1) policies and strategies, (2) strategic planning tools, (3) public perception and participation, (4) performance indicators, and (5) hydraulic boundary conditions and safety standards. In the evaluation studies, the state of the art in the 5 countries is established and evaluated. Based upon the evaluation, recommendations for improvements are being developed. In the four case studies, state of the art risk analyses (Hall et al., 2003; Jorissen et al., 2001; Oumeraci and Kortenhaus, 2002) are being conducted in Flanders, Ribe, Lincolnshire and Langeoog. Based on integral inventories of physical and socio-economic conditions as well as existing coastal defence measures, risk assessments are carried out, and recommendations for common (balanced) measures to reduce the risk of flooding are being established.

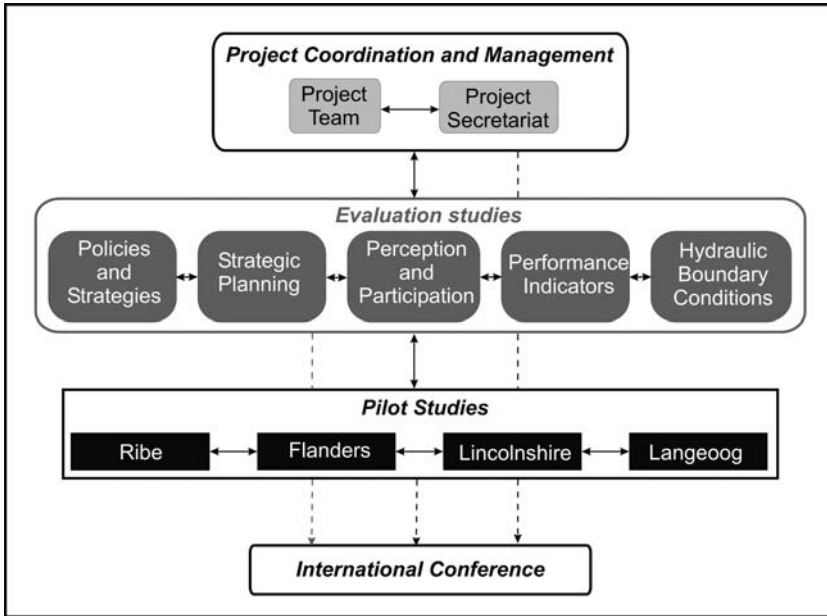


Figure 2. COMRISK project structure

The case and evaluation studies are being conducted during the main phase (2003–2004) of the project, most of them by subcontractors. Below, first results of subprojects 1 and 3 are described.

3. SUBPROJECT 1 – POLICIES AND STRATEGIES

Subproject one started with the definition of an analytical framework as a tool to properly assess the policies and strategies in the 5 participating countries (RIKZ 2004). A distinction in the framework between the *context* and *policy* has been made (Figure 3). In the context elements are present that are important to the governments of the regions. The government has to manage within this context and cannot directly influence this. Choices are made in the elements of the *policy*, including the setting of goals (a strategic element). Using this framework, an inventory was made of different levels (strategic, institutional, instrumental and operational) of coastal risk management in present policies of the 5 countries. This inventory formed the basis for an assessment of the present policies in terms of legal, social, technical, financial, socio-economic, ecological and managerial aspects. In the policy assessment, focus points on the basis of the ICZM-criteria as formulated by the European Commission (COM/2000/547) have been used. These principles offer various ways of good coastal zone management. Both the inventory and the

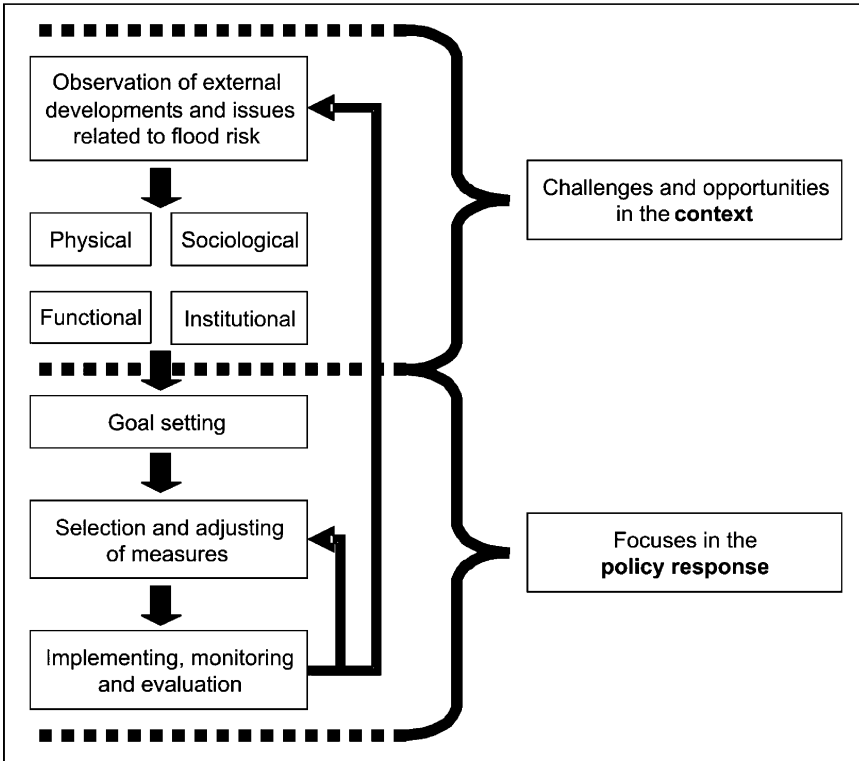


Figure 3. Analytical framework

assessment were realized through literature research as well as interviews with experts and policy-makers.

In assessing the context, the subproject analysed which challenges policy-makers face. Challenges can be threats to be confronted or avoided, but also opportunities to be explored and possibly exploited. Three significant external developments have been identified (Figure 4). All countries regard climate change and the corresponding sea level rising as major challenge. Ecological regulation is a complicating factor to policy-making, but in most cases not regarded to be a major challenge to the existing policy. Regarding the physical system, it is concluded that the German coastline offers the least natural protection. The Dutch physical context is both in absolute and relative terms the most challenging, though it has some protective dunes. In the Netherlands major cities are situated entirely in flood-prone areas. Hamburg and London are partly situated in potentially flood-prone areas. Almost all policymakers are confronted with sensitive natural habitats at their coast, which brings along limitations and conditions to coastal defences. Development pressure is a major issue for the Netherlands and England.

		UK	B	NL	Nds	HH	SH	DK	
External developments		Climate change	X	X	X	x	X	X	X
		Ecological regulation	x	x	x	x	x	x	x
		Development pressure	X	x	X				
Analysis of the coastal system	Physical	Large flood-prone area	x	x	X	x	x	x	
		Deep flood-prone area	x		X	x	x	x	
		Coastline offers little protection	x		x	X		X	x
	Functional	Urban areas	x		X		X		
		Designated nature areas	x	x	x	x		x	x
	Sociological	Low sense of urgency citizens	X	X	X	x			
	Institutional	Limited staff capacity		X					
		Limited budget	X	x	x	X	x	x	
		Limited relation to disaster pol.		x					
		Limited relation to spatial policy		x					
Limited vertical integration									
Risk judgement and goal setting		Time horizon	X		X				
		Economics taken into account	X		x			x	x
		Ecology taken into account	X	x	x	x	x	x	x
Measures		Allowing dynamics	X	x	x				x
		Local tailor-made solutions	X	X	X		x		X
		Variety of interventions	X				x		X
		Variety of man. Instruments	X		x		x		X
Monitoring and evaluation		Reconsidering instruments	X	x	x				
		Monitoring of instruments	x	X	X	X	X	X	X
			x = challenge / focus point X = major challenge / major focus point						

Figure 4. Assessment overview

With regard to societal perceptions and attitudes towards flooding, the common challenge policy-makers experience in England, Flanders, the Netherlands, and to a lesser extent Niedersachsen, is to raise the sense of urgency among their citizens to make them either support governmental action or take action themselves. In Schleswig-Holstein, citizens are also noted to have low risk awareness, but this has not lead to practical difficulties in implementing policy. Hamburg and Denmark in general feel that the demand and support for action is about right. In the institutional context, limited budget is a common challenge for policy makers in all countries. The challenges regarding integration of policy fields and levels, is more ambiguous. To some policy fields the links are not strong, but often the primary policy-makers do not consider this as a major problem. The vertical integration in

England has improved according to all interviewees, however at the local level a 'national policy vacuum' is experienced.

In the policy assessment, (major) focal points have been identified within the analytical framework (Figure 3). One aspect that was assessed is the risk judgement and (strategic) goal setting in the 5 countries. England and the Netherlands have a multi-generation time horizon in common. Both countries have explored the long-term demands for coastal protection. The other countries generally have limited themselves to study how – in the long run – the current level of protection could be maintained. England has a strong focus on calculating costs and benefits; for every project a benefit/cost ratio is calculated. In the Netherlands and Denmark current standards have been set decades ago with much consideration to costs and benefits and are currently being updated. Hamburg and Niedersachsen (in the Weser-Ems region) have done some quantification of damage potentials. However, as now the dike design regulation does not distinguish between protection levels, this aspect cannot be directly incorporated in decision-making. Schleswig-Holstein has incorporated this type of information in setting priorities in implementation. The way the ecological carrying capacity is taken into account is quite similar in the 5 countries, as EU law regulates matters such as the Environmental Impact Assessments and the protection of habitats. Concerning risk reducing measures, England, Denmark, and to some lesser extent Hamburg use a variety of measures to achieve their goals. Flanders, the Netherlands and the other German states concentrate mostly on coastal defence. The Netherlands, though focused on coastal defence, is also more and more searching for multiple ways to arrange their coastal defence. With respect to implementing, monitoring and evaluation, all countries try to improve their actions by learning about their performance. However, only few countries are reconsidering their general set of measures or have done so recently.

Based on the analysis, it is recommended to further the co-operation in coastal risk management in the NSR by, for example, the definition of a common vision (on a strategic level) for coastal risk management, or by the establishment of a partnership which stimulates knowledge exchange between the countries. Acknowledging the large variance in the context among the countries, this does not necessarily have to lead to harmonisation or, rather, one common EU-policy. Although future harmonisation of policies and strategies should not be avoided when desirable and feasible, it is concluded that policy makers should, primarily, focus on mutual understanding and mutual learning.

4. SUBPROJECT 3 – PUBLIC PERCEPTION AND PARTICIPATION

In this subproject, an assessment of the public perception and participation in the 5 countries was carried out. Based on this analysis, recommendations to improve the awareness of the risks of coastal flooding in the population as well as the active involvement of the population in the planning process were developed. The study

was realized through literature research, an expert workshop, an opinion poll, and an expert survey (Kaiser, et al. 2004).

During the workshop, experts from the participating countries presented and discussed the state of the art on public perception and participation in coastal risk management. A Dutch study resulted in a general feeling of safety of the coastal population (Elnterman et al. 2003). The river floods of 1993 and '95 resulted in strong but short-lived increases of risk awareness in the population. It turned out that risk can be defined or perceived in different ways: the quantifiable technical risk applied by administration (e.g. return intervals, probability of breaching), and the subjectively perceived risk in the population (will my house be damaged). Another Dutch study on risk perception (RIKZ and BWD, 2002) delivered recommendations on how to improve risk communication, e.g., information should be objective and from a trustable local institution, pictures say more than words, and the flow of information should be continuous and locally focussed. A study in England (J. McCue, pers. comm. 2003) showed that only about 55% of affected population is aware of living in a flood-prone area. People tend to ignore or disclaim the risk for personal or financial reasons. Like the Dutch RIKZ and BWD study (2002), it is recommended to use existing local communication structures and persons (local champions) to communicate risk. Finally, a German study on risk perception that was carried out in a coastal region in Lower Saxony (Peters and Heinrichs, 2003) underlined the general feeling of safety in the coastal population. However, there is scepticism about the ability of the coastal defence system to cope with climate change. In this context, 30 to 50% of the interviewed local residents support the reinforcement of coastal defence structures.

The opinion poll was conducted in 5 regions: Ribe (DK), St. Peter-Ording (G), Sluis (NL), Oostende (B) and Skegness (UK). In all, 2,000 questionnaires were randomly distributed to private households, 411 of which were returned. Of all respondents, 32% were female and (only) 7% younger than 30 years. The highest return rate (28%) was recorded for Oostende where a public discussion about a comprehensive coastal defence measure is underway. From the answers, it appeared that the experience of a disaster and/or the knowledge about risk does not automatically imply awareness of the consequences and own concernment (i.e., precautionary actions). Although all selected households are situated within flood-prone areas, 30% thought that their house could not be inundated during storm surges. For the Netherlands this ratio amounted to 10%, for Denmark to 68% (Figure 5). The answer to the question: "how well have you been informed about the basic risks of a storm flood by the responsible authorities", resulted in a felt information deficit. Apart from Ribe, where 79% seem to be satisfied with the information policy of the authorities, more than half of the respondents answered to be low or very low informed (Figure 6). Hence, an information deficit became apparent.

Apart from more information, the respondents demanded more active involvement in the process. However, if asked about concrete actions, (only) 6% would be willing to sacrifice one working day, 9% would work regularly as a volunteer, whereas about 50% would visit an information event (Figure 7).

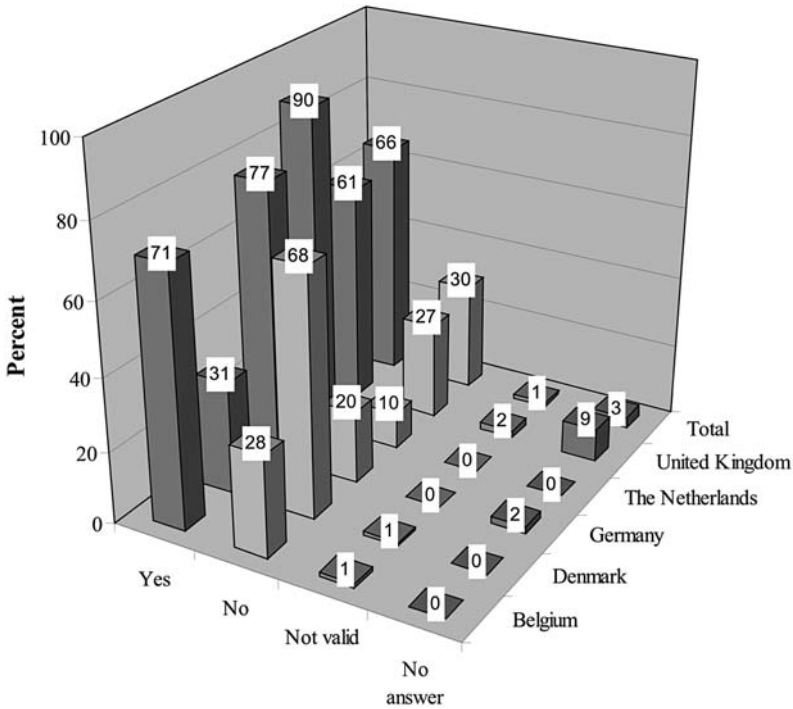


Figure 5. Response to the question: could your dwelling be hit by the floodwater in case of a coastal flooding?

From the expert survey it became clear that (good) information is as important as participation. Further, whereas participation does increase acceptance for coastal risk measures, it causes significant effort with administration. The answers revealed that there is no ideal information and participation tool. Each process needs to be individually adapted.

The analysis resulted in a number of recommendations to improve the awareness of the risks of coastal flooding in the population as well as to further active involvement of the population in the planning process. For example, more information about coastal risk management should be supplied. It should be targeted (but honest), neutral, comprehensive and understandable (science translation). A mix of information tools, especially local media and “local champions” (e.g., firemen), should be used. Concerning participation, the instruments should be tailored to the specific problem, the subject and to local conditions. In general, a mix of targeted instruments should be applied. The level of participation as well as the people and organisations to be involved should be decided upon in an early stage. Their input should be valued and translated into real decisions. Independent persons (consultants) should moderate the procedure and, finally, a good and open communication should be mandatory during all phases.

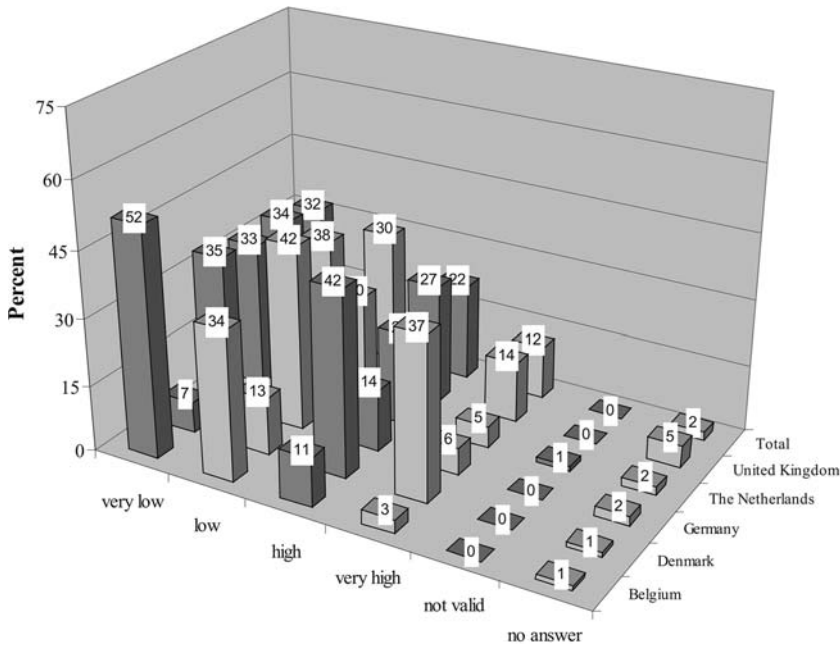


Figure 6. Response to the question: how well have you been informed about the basic risks of a storm flood by the responsible authorities?

5. DISCUSSION AND OUTLOOK

COMRISK presents a challenge for public authorities in the NSR working on coastal risk management. It is the first time that national and regional authorities work together in a transnational project. Single authorities have been involved before in international projects on coastal risk management, e.g., under the EU-program MAST. These were, however, research projects, focussing on technical aspects, and with research institutes as partners. In the EU Demonstration Programme on integrated coastal zone management, the focus was not so much on coastal risk management but, in a broader and more integrated approach, on sustainable development along the coasts. Coastal risk management authorities have, on the strategic level, clearly defined national/regional responsibilities and competencies (ending at the border). Hence, authorities as well as governments might be sceptical and reluctant to have other (foreign) authorities evaluate their national/regional strategies. On the other hand, neither do the coastal lowlands in the NSR end at national borders, nor do the problems, for example sea level rise. Further, as expressed in the program targets for INTERREG IIIB (see above), the EU encourages the development of compatible strategies and common identities for its regions. These arguments call for transnational co-operation and co-ordination.

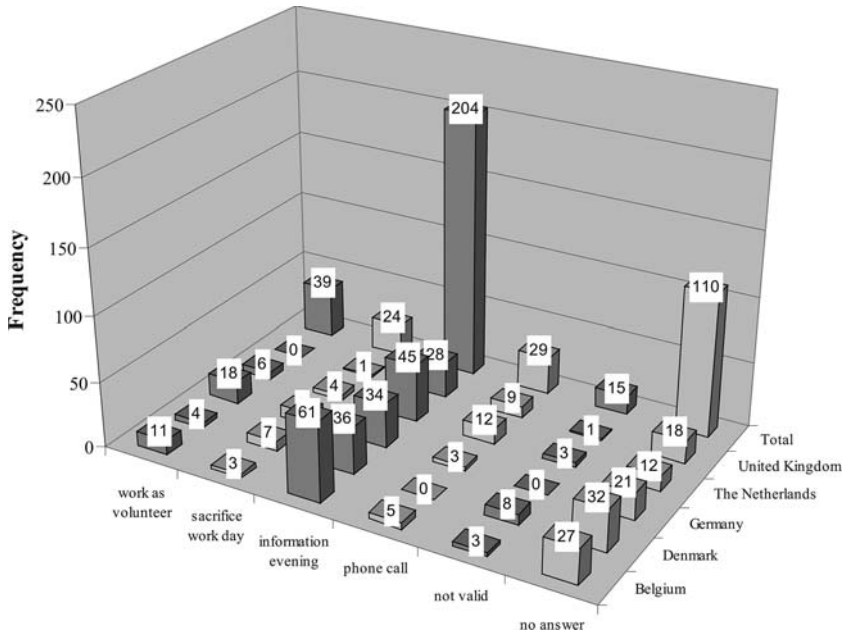


Figure 7. Response to the question: if you want to represent your opinion in coastal defence planning, what would you like to do?

Transporting this discussion to COMRISK, one of the main bottlenecks is the evaluation of national methods, instruments, strategies and policies. It would be undiplomatically to rank “good and bad” countries in such an evaluation. The “hazard” of this happening is not as high as it might appear *prima facie*. Boundary conditions for coastal risk management differ considerably in the countries of the NSR (see Ch. 3). Taking this into consideration, an optimal solution in country X might very well be counterproductive in country Y and vice versa. A SWOT analysis considering these varying national boundary conditions (geography, history, society) gives objective outputs.

The public perception of storm surges as a hazard, or coastal risk management as an important issue, is not satisfactory in the NSR (see Ch. 1 and 4). Other problems like unemployment and (economic) stagnation being more exigent. Consequently, it might become increasingly difficult to convince population as well as government of the necessity to invest in coastal defence. The outcomes of COMRISK will supply national and regional coastal risk management authorities with an overview of present circumstances in the NSR. On the basis of this overview, they will be enabled to choose optimal national/regional solutions, including awareness raising for the risks in coastal lowlands. Further, COMRISK will inform policy of coastal risks and the most effective strategies for combating them. Finally, the results of COMRISK

will demonstrate the European Union that coastal risk management in the NSR is not an isolated effort, but a well integrated and co-ordinated common endeavour.

ACKNOWLEDGEMENTS

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CHAPTER 6

DIKE INVESTIGATIONS USING GEOPHYSICAL METHODS – TECHNIQUES FOR THE FUTURE?

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Abstract: Investigation to provide information about the location and extent of potential mechanically weak and permeable zones of flood defences is a necessity for effective flood defence management. Geophysical techniques are well suited to detect such zones and are themselves non-destructive. An initial investigation can quickly locate problem areas, and a secondary investigation can provide detailed information about the type and extent of the problem. In emergency situations the results of such investigations would allow the optimum location and planning of emergency repair and strengthening works. The investigative techniques can also be employed in post-flood activities to ascertain the extent of damage inflicted during floods, or as part of a long-term flood defence monitoring programme. JOANNEUM RESEARCH has undertaken work to investigate the potential of various geophysical techniques for application in dike investigations. The geophysical techniques have been tested at pilot sites on actual dikes, which concerning the physical characteristic of the hydraulic situation can be divided into two categories: dikes that constantly withhold water (water on one side and air on the other) and dikes that only withhold water in extreme flood situations (air on both sides). Several geophysical techniques were tested and optimised: infrared, ground penetrating radar, and electromagnetic for initial overview investigations; and 2D or 3D geoelectric surveys to provide detailed information in a secondary survey. The results of the geophysical measurements demonstrate that geophysical methods can be successfully employed to investigate dikes, delivering important information about the homogeneity or inhomogeneity of dikes. Particularly, inhomogeneous areas such as leakages and have been detected and validated

Keywords: flood defence, dams, dikes, geophysics, infrared, ground penetrating radar, electromagnetic, geoelectric

1. INTRODUCTION

Investigation of flood defences to provide information about the location and extent of potential mechanically weak and/or permeable zones is a necessity for effective flood defence management. Increasingly, geophysical methods are being applied to tackle this problem, however it should be noted, that the required information (e.g. weak or permeable zones, water saturation, etc.) is not detected directly, but are derived from the result of the geophysical measurement.

For example, Figure 1 shows the result of a geoelectrical measurement of a dike and his subsurface. The horizontal bar illustrates the values of the resistivity and under this coloured bar, there are arrows indicating the grain size and the permeable and the impermeable regions.

Geophysical methods rely on differences in rock and soil properties, or indications of various physical processes occurring underground. Dependant on the problem that requires investigation a suitable geophysical method- or a combination of methods must be selected.

For the investigation of dikes different geophysical techniques (e.g. infrared, ground penetration radar, electromagnetic,...) have been tested by JOANNEUM RESEARCH at pilot sites and actual dikes. Figure 2 shows a GPR measurement,

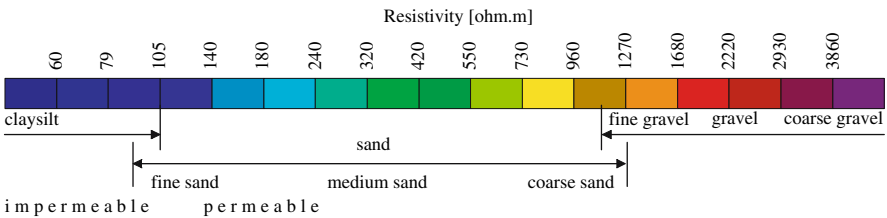


Figure 1. Result of geoelectric measurement and interpretation



Figure 2. GPR measurement (200 MHz antenna)

Figure 3 an electromagnetic measurement and Figure 4 a multielectrode geoelectric measurement.

The dikes investigated can be divided into two categories with respect to the hydraulic and geotechnical situation at the time of investigation:

- Case A – dikes that constantly withhold water, that is with water on one side and air on the other; and
- Case B – dikes that only withhold water in extreme flood situations, and thus are investigated with air on both sides.

For Case A, suitable geophysical methods are those which are sensitive to zones with locally increasing water content (such as resistivity or geothermal measurements) or which respond to water flow underground (such as self potential/streaming component and infrared measurements). For Case B, geophysical methods that identify weak zones displaying local increasing porosity or channelling would be recommended (such as resistivity or georadar measurements).



Figure 3. Electromagnetic measurement with EM31



Figure 4. Multielectrode geoelectric measurement

2. DESCRIPTION OF METHODS TESTED

2.1. Overview

The geophysical methods tested at Case A or Case B sites were divided into two categories: those suitable for an initial investigation, and those suitable for a secondary investigation. Initial investigation techniques should be capable of measuring large lengths of dikes in a short time, thus allowing an overview of dikes to be obtained. Non-homogeneous areas of dikes should be quickly identified, and then studied in more detail using a secondary investigation method. The secondary investigation techniques should be able to characterise the inhomogeneous zones. Table 1 provides an overview of the geophysical methods that were tested.

2.2. Methods

2.2.1. Infrared

Infrared pistols and cameras register and measure infrared radiation, which is displayed as a surface temperature. The pistol provides surface temperature at single points, whereas the camera produces a high-resolution 2D thermal picture.

The potential of using infrared methods in flood defence surveys has not yet been fully researched. The great advantage of infrared measurements over many other geophysical techniques is that they can be carried out from a car or even an airplane, and thus extensive lengths of dikes can be measured extremely quickly.

There are two known hindrances to the use of infrared measurements for dike investigations. Firstly, infrared cameras measure surface temperatures, and thus weaknesses within the dam body are only detected if the problem is sufficiently severe to produce a change in surface temperature. This also means that dams can only be investigated whilst they are retaining water. Secondly, the surface material of the dike strongly influences the readings. The controlling property is the emission coefficient of the surface material. As part of the investigations an experimental device was developed to determine the influence of different materials. Table 2 shows some results:

2.2.2. Ground penetrating radar (GPR)

A high frequency (MHz) electromagnetic signal propagates from an antenna into the subsurface with a velocity that is dependent on the relative permittivity of the subsurface material. At material boundaries the signal is partly reflected. The

Table 1. Overview of geophysical methods tested for various types of dike investigation

Case	Investigation type	Geophysical methods tested
A	Initial, overview	Infrared, electromagnetic
	Secondary, detailed	Electrical resistivity, self-potential, infrared
B	Initial, overview	Ground penetrating radar, electromagnetic
	Secondary, detailed	Ground penetrating radar, electrical resistivity

Table 2. Emission coefficients of different surface conditions

	Emission coefficient values		Influence of water content
	Dry	Wet	
Gravel	0.93	0.93	—
Earth	0.94	0.94	—
Sand	0.90	0.90	—
Grass-long	0.82	0.87	+
Grass-short	0.86	0.88	+

antenna registers the reflected signal and displays it as a radargram, from which information about the subsurface can be gained. The vertical resolution (0.1–1 m) and the penetration depth (2–20 m) vary according to the antenna frequency used and the subsurface conditions.

GPR measurements are extremely useful for investigating the structural composition of the dam body and to locate inhomogeneous regions along the embankment's length. They can be carried out by a single person on foot, or with two people from a vehicle, and thus large distances can be measured in a relatively short time.

2.2.3. *Electromagnetic*

Electromagnetic fields are also used for further geophysical measurements, albeit at lower frequencies (kHz) than for GPR measurements. An alternating current is passed through a transmitter coil, which induces a primary magnetic field in the subsurface. Eddy currents are generated in the ground, which in turn produce a secondary magnetic field in conductive bodies. The secondary magnetic field is recorded by the receiver in terms of subsurface conductivity, allowing clayey areas to be distinguished from sandy/gravelly regions.

Depending on the type of electro magnetometer used, the penetration depth of measurements is between 0.6 m and 60 m. Surveys can be carried out at a walking pace with one or two people. Using the EM 31 or the EM 38 electro magnetometer it is also possible to measure the inphase component, which is useful for detecting buried metal objects.

2.2.4. *Geoelectric resistivity, and self potential*

For geoelectric resistivity measurements a low frequency electric current is passed through the ground between two electrodes. A further two electrodes measure the potential difference at the surface, which is dependant on the conductivity of the subsurface. By altering the spacing and geometry of the four electrodes it is possible to investigate different subsurface zones and, using an inversion algorithm, to derive the spatial distribution of the specific electrical resistivity. The specific electrical resistivity of the subsurface depends on the type of material, permeability and water saturation. Low specific electrical resistivities point to a high fines content (clays)

and thus areas of water retention, whereas porous materials such as sands and gravels cause high specific electrical resistivities. Thus the structure and homogeneity of the dam can be investigated.

The depth of investigation is dependant on the number of electrodes, their configuration and spacing, and the subsurface conditions. The resolution is primarily dependant on the electrode spacing and configuration. Using multielectrode equipment many electrodes are laid out along a profile, and a computer controls which four electrodes are active at any given moment. In this way it is possible to collect information quickly and efficiently with one or two people.

There are further special types of geoelectric measurement, one of which is Self-Potential (SP). Naturally occurring background potentials are measured, which are likely to relate to the flow of water through capillary systems (streaming potential component of SP). Two non-polarisable electrodes are used, the base electrode being placed in an undisturbed area whilst the other is moved around the area of interest. The difference between the two measured self-potentials is then plotted to locate anomalous areas, which are used to identify zones of concentrated seepage in the dike.

3. RESULTS OF TEST MEASUREMENTS – CASE A

3.1. Pilot Site St. Dionysen

3.1.1. Site description

Initial infrared and geoelectric test measurements were carried out on an intact embankment dam belonging to Austrian Hydro Power near St. Dionysen in Styria, Austria. The embankment dam retains the inflow water to a hydro power station and was constructed using excavated soil from the surrounding area. It is sealed on the waterside with bitumen textile. The 100 m stretch of embankment in the study area includes a known inhomogeneity, namely a drainage pipeline.

3.1.2. Infrared measurements

Infrared measurements were taken using both an infrared pistol for point measurements, and an infrared camera for spatial measurements. The results were relatively constant at a cool temperature (approx. -1°C), with the exception of the drainage pipeline, which could clearly be seen as an inhomogeneous warmer area (approx. 3°C) suggesting water. The camera quickly provided an overview of the surface temperature of the area. More detailed information was gained from this picture along selected profile lines using the accompanying software.

3.1.3. 2D/3D geoelectric measurements

2D geoelectric measurements were made using a multi-electrode apparatus along three 100 m longitudinal profiles (dike crown, mid-side, and dike base) with an electrode spacing of 1 m, and along two 40 m cross profiles with the electrodes spaced at 0.75 m. In each case data from Dipole-Dipole, Pole-Dipole, Schlumberger,

and Wenner Alpha configurations were recorded. A Pole-Pole 3D measurement was made in the vicinity of the drainage pipeline with electrode spacing of 2 m and 1.5 m on ten longitudinal and five cross profiles respectively.

The high resistivities measured in the 2D and 3D geoelectric surveys confirmed that the dam is dry and thus intact. The results also verified that the dam was built from the same material as the surrounding area, namely mainly gravel with some clay. Figure 5 shows the results of the 3D geoelectric measurements with a portion cut away to clearly reveal the effect of the drainage pipe and a clay formation.

3.1.4. Self-potential measurements

Two Self-Potential measurements were also carried out at the pilot site. The near constant results demonstrated that, as expected, the embankment dam does not leak.

3.1.5. Remarks

The infrared and geoelectric measurements confirmed that the dam was intact, and located the known inhomogeneity. The methods were tested further at a different pilot site in Spielfeld/Straß.

3.2. Pilot Site Spielfeld/Straß

3.2.1. Site description

The second set of test measurements were made on another embankment dam (see Figure 6) retaining water leading to a power station belonging to Austrian Hydro

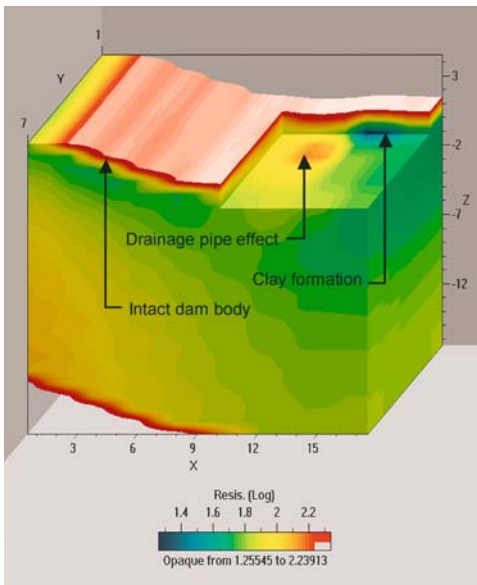


Figure 5. Pole-Pole 3D geoelectric results



Figure 6. Pilot site Spielfeld/Straß

Power. In the pilot site area the dam was known to leak, as water could be seen seeping from the dike on the landside, but the exact leakage path through the dam was unknown.

3.2.2. Infrared measurements

The infrared results clearly identified the seepage zone, using both the infrared pistol and camera. Figure 7 shows a thermal picture obtained using the camera. The dike side (green/yellow) with tree trunks (red rectangles) can be clearly distinguished from the warmer roadway running along the base of the dike (cream). In the middle of the picture the coldest region represents the seepage zone (blue), with water also present on the road. The camera also identified a previously undetected seepage zone outside of the study area. This highlighted the potential of infrared measurements for an initial dike survey.

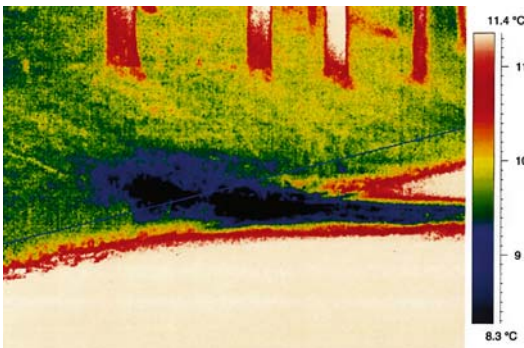


Figure 7. Pilot site Spielfeld/Straß

3.2.3. 2D/3D geoelectric measurements

Four 40 m 2D geoelectric longitudinal profiles were measured using various configurations with electrode spacings of 1.0 m on the dike crown and 0.8 m on the dike slope and base. The results clearly showed the water-saturated zone in all profiles as areas of low resistivity. A smaller seepage arm was also identified.

Two 3D measurements were also undertaken, one on the dike crown using a Pole-Pole configuration, and the other on the dike side with Pole-Dipole configuration. In both cases the electrodes were spaced at 1.6 m. The Pole-Dipole measurement was found to provide the best results. Figure 8 shows the results of the Pole-Dipole measurement, with a block of results removed to reveal the inside of the dike at the seepage zone. A zone of low resistivities (blue) could be seen through the whole dike body, which clearly identified the leakage path. The end of this zone on the landside corresponded to the location where seepage could be seen.

3.2.4. Self-potential measurements

Self-Potential measurements were also undertaken, with the base electrode placed in the water leading to the power station. In Figure 9 the band of anomalous values (red) clearly show the seepage path, with the small second seepage arm identified by the 2D geoelectric survey.

3.2.5. Remarks

Infrared measurements offer a fast method of locating leaks, which can be examined in detail using geoelectric techniques. However infrared techniques can only be

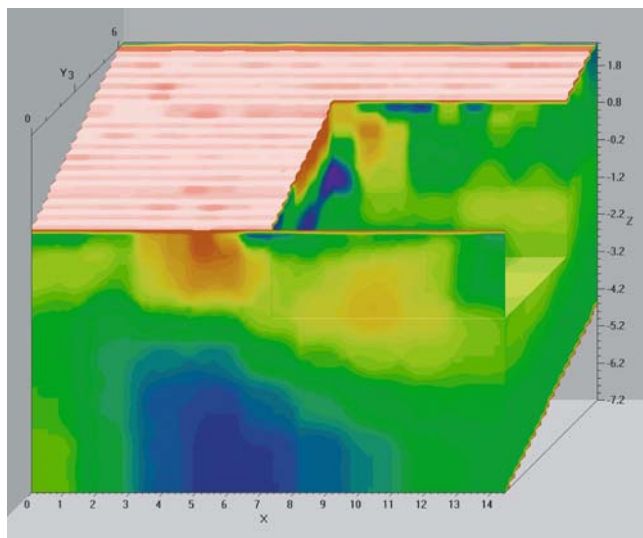


Figure 8. Pole-Dipole 3D geoelectric results

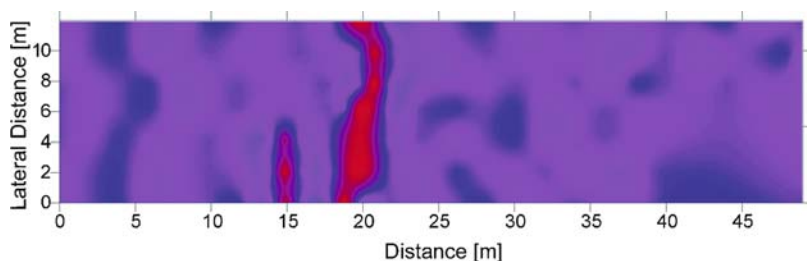


Figure 9. SP distribution as 2D plot

employed on dams where water is present on the waterside. For this reason radar and electromagnetic techniques were tested at a third pilot site on a dry dike, which only retains water in an extreme flood situation.

The results of the geoelectric measurements demonstrated that a multielectrode survey (2D/3D) and Self-Potential investigation is highly suitable to determine the exact seepage path of a dike leak.

4. RESULTS OF TEST MEASUREMENTS – CASE B

4.1. Pilot Site Lobau

4.1.1. Site description

Two stretches of dike, which enclose the oil harbour in the Lobau region near Vienna, were investigated. The dike is set back from the harbour, and only retains water in extreme flood situations, thus air was present on both sides of the dam during the investigation.

Stretch 1 (see Figure 10 and 11) was 1 km long and practically straight. During the catastrophic floods in 2002 seepages occurred over about 60 m of this stretch, and large stones were placed along the foot of the dam on the landside for stability. A metal manhole cover and a flight of steps are located on the dam midway along the stretch. Ground Penetrating Radar and electromagnetic overview measurements were carried out over the whole stretch, and a 2D geoelectric detailed investigation was undertaken over a 120 m length of dam that included the stretch where seepage had occurred.

Stretch 2 was located on a sharp bend in the dike. During the 2002 floods no seepage was visible through the dam, but a piping developed beyond the dam on the landside. Four geoelectric profiles were measured to try and identify a seepage path leading to the spring.

4.1.2. Overview measurements on stretch 1 – radar, electromagnetic

For the radar measurements a SIR-2 (GSSI/USA) instrument was used with 100, 200, and 400 MHz antennae. The antennae were towed behind a car, and the entire



Figure 10. Pilot site Lobau

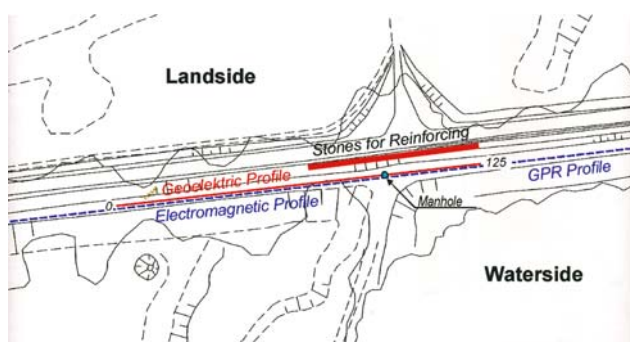


Figure 11. Plan of stretch 1 (detail)

stretch was measured along the dike crown a total of six times – once in each direction with each of the antennae.

Electromagnetic measurements were made at approximately 1.5 m spacing on the dike crown along the whole stretch using an EM 31 (Geonics/Canada) instrument with a penetration depth of up to 6 m.

The processed data from one of the 200 MHz measurements is displayed as a radargram under the electromagnetic results in Figure 12. Both show data from the whole of Stretch 1. The portion of Stretch 1 that was investigated in more detail (see Figure 13) using geoelectric methods is also shown between the red dotted lines. Based on the results of the GPR and electromagnetic overview measurements it was possible to divide Stretch 1 into the homogeneous and inhomogeneous regions I-VII.

In *Region I* the dike has a homogeneous composition; the boundary between dike and subsurface at 6 m depth is barely visible in the radargram. The results in *Region II* are also fairly homogeneous; the radargram shows a clear dike structure

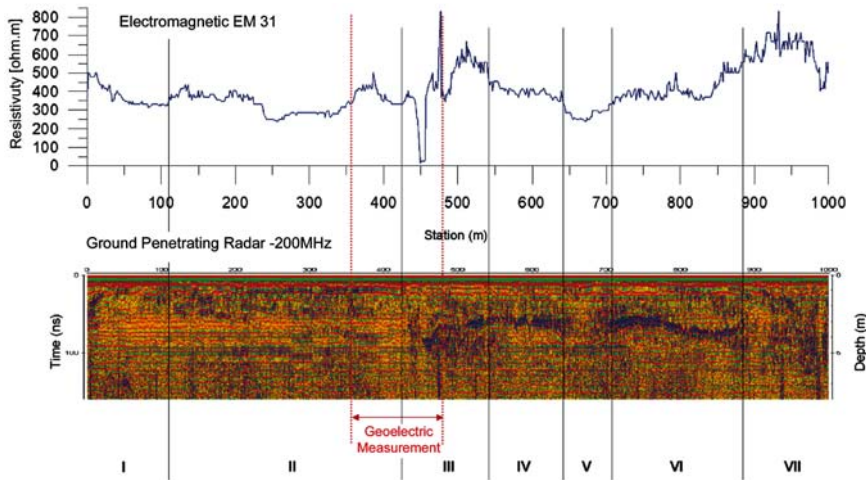


Figure 12. Results from electromagnetic and GPR (200 MHz) investigations

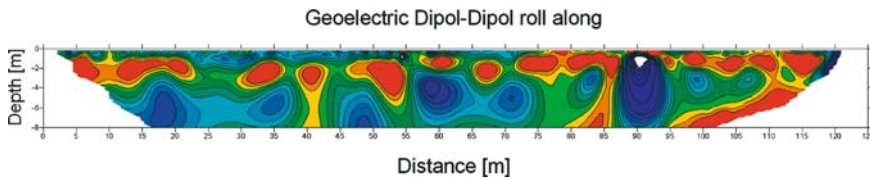


Figure 13. Result from detailed geoelectrical investigation, stretch 1

in the uppermost 3 m and a boundary between dike and subsurface at 6 m depth; the electromagnetic results show higher specific electrical resistivities at the start and end of the region than in the middle, which is probably due to variations in the dam material with higher values representing a lower fines content. *Region III* represents a very disturbed and inhomogeneous zone; the effects of the manhole cover (with iron installations) and a concrete stairway, located at 450 m and 480 m respectively, on the results can be clearly seen; from approximately 500 m onwards a strong reflection boundary is present at 3–4 m depth in the radargram. *Region IV* is again a homogeneous stretch of dam; the strong reflection boundary from *Region III* continues at 3–3.5 m depth. The results in *Region V* are also homogeneous, with lower specific electrical resistivity values from the electromagnetic survey demonstrating a change in dam material, with more fines content than in the neighbouring regions; the reflection boundary is no longer present. *Region VI* has similar characteristics to *Region IV*. The results from the final *Region VII* are relatively inhomogeneous; the clear reflection boundary at 3–4 m depth is not present on the radargram, and high specific electrical resistivity values from the electromagnetic survey point to a low fines content.

4.1.3. Detailed measurements on stretch 1 – geoelectric

Four geoelectric profiles were measured using a SuperSting R8 IP (AGI/USA) Instrument. Results from a Dipole-Dipole configuration were recorded for each profile, and on three of the profiles a Wenner-Alpha and/or Schlumberger configuration was also tested. Both standard and roll-along techniques were employed.

Figure 13 shows the result of a measurement on the dike crown using an electrode spacing of 1.5 m. Effects from the manhole were clearly visible at 90 m in the processed geoelectric profile. It is to note that in the zone where seepage had occurred (from 70 to 120 m) higher resistivities close to the surface were recorded. This could be due to a lower fines content than in the neighbouring zones, due to fines being washed out by seepage.

4.1.4. Detailed measurements on stretch 2 – geoelectric

Measurements were taken on four geoelectric profiles (see Figure 14): on the dike crown and dike foot (landside) before the bend, and at the dike foot and below the access road after the bend. Figure 15 shows the processed sections from the two profiles measured at the dike foot. The red zones at the base of the sections represent zones with low resistivities, which is an indicator for permeable material. This could represent a seepage pathway (red dotted line, probably an ancient river bed) beneath the dam on both sides of the bend, the continuation of which leads directly to the piping.

4.1.5. Remarks

The investigations undertaken at pilot site Lobau demonstrated that GPR and electromagnetic measurements can be successfully used to perform an initial overview survey. The survey can be carried out at walking/driving pace with one or two people. These methods can be employed regardless of whether the dike is currently



Figure 14. Plan of stretch 2

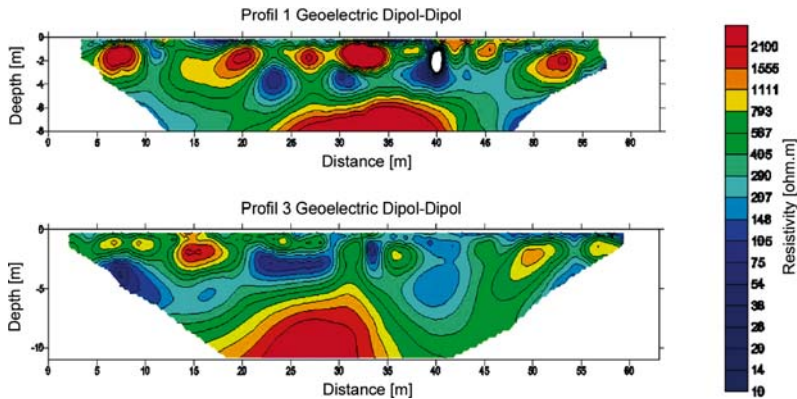


Figure 15. Results from geoelectrical investigation

retaining water or not. The results of the survey can be used to divide the dike into homogeneous and disturbed regions. This is helpful for determining which regions of dike should be studied in more detail using a geoelectric survey. If geotechnical test probes are to be taken, then an overview survey would provide an excellent method of deciding the optimum location for probes. Otherwise probes are usually taken at regular intervals, which runs the risk of completely missing a region, or situating more probes than necessary in a homogeneous region.

On the basis of the results of the measurements at the pilot site Lobau 50 km of embankment dams along the Danube River were investigated in spring and summer 2004. To get an overview 50 km of GPR survey were carried out using 200 and 250 MHz antennas. For detailed information on selected sections of the dam geoelectrical measurements using a Dipol-Dipol electrode configuration were undertaken.

The results of the geophysical survey provided a basis to optimise the locations for the geotechnical investigation program.

A final appraisal of results is not completed yet, so it is not possible to publish the results in this paper. But at this stage of the final interpretation it can be stated that the geophysical investigation were an important part of the project.

5. CONCLUSIONS, BENEFITS AND LIMITATIONS

Geophysical methods are non-destructive methods for the investigation of the underground – they are economical and fast, they cover profiles or areas. But all the methods are “indirect methods”.

The results are presented in terms of physical rock or soil properties or structures in the underground and must be transformed into geological or geotechnical information. Therefore such investigations are most effective in combination with “direct methods” such as geotechnical testing, sampling, or drilling. The implementation of geophysical methods into a program of site investigation will increase the efficiency. Depending on the individual dike under consideration, various

geophysical techniques can be used to provide both a fast overview, or more detailed information about inhomogeneous zones. This allows an optimised design of following detailed direct methods.

The methods tested in these studies are suitable both in emergency flood situations, or as part of a long-term dike-monitoring program. An important further step would be to develop the measuring equipment and the interpretation methods of geophysical data specifically for dike measurements.

The studies confirm as an efficient concept of investigation the following way

- fast geophysical site investigation with radar or geoelectrical measurements in order to select homogeneous parts of the subject
- detailed investigation with a combination of special methods with high resolution to verify the geophysical indication
- derivation of a geotechnical investigation program based on the geophysical result and optimised with respect to zones with anomaly physical properties
- geotechnical investigation and verification of the geophysical prediction.

The potential efficiency of any geophysical investigation is based on the logic implementation of such tools like ground penetrating radar and geoelectrical measurements in an investigation strategy; the goal is to support and optimise geotechnical investigations – not to replace.

Unfortunately, research to date is usually carried out by small individual groups who have limited resources, and there is little or no collaboration with other groups carrying out similar work. Progress is therefore understandably slow, and the full potential of using geophysical techniques for dike investigations will not be realised until there is more worldwide co-operation.

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SECTION II

FLOOD EVENTS AND IMPACTS

CHAPTER 7

THE ENVIRONMENTAL IMPACT OF FLOODING OF THE DUTCH 'DELTA-METROPOLE'

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Abstract: Model studies into the consequences of flooding events usually focus on damage to buildings, infrastructure, economic losses and casualties yet ignore the risk of environmental damage. In this project, a model study was made to assess the environmental consequences of the release of pollutants during the flooding of a polder district in the Netherlands following a river dike breach. A conceptual framework was established for the sequence of events or 'chain reaction' during a flood. A 250 m wide dike breach is formed, the scour of the flood waters and/or high water levels may damage or destroy objects like homes, industrial complexes and farms; damaged objects release hazardous substances such as suspended matter and chemicals that will be dispersed in the flood waters and will affect people and ecosystems in the inundated area. The analyses were made in the 50,000 ha case study area 'Krimpen', located in the western Netherlands near the cities of Rotterdam, Delft and The Hague. The simulated period of flooding was ten days. The failure of objects where hazardous chemicals are stocked was linked to water height and -velocity. The release and migration of pollutants like volatile aromatics, germs, sum PAH, PCB, LNAPL, DNAPL, heavy metals, nutrients and pesticides was simulated with an innovative, integrated modelling tool. The novelty of the method required the collection of large numbers of data that had not been compiled earlier. More than once data were obtained through expert opinions and best estimates. The assessed impact of the pollutants on the environment was found to be substantial. Small yet numerous sources like cars may release substantial amounts of toxic chemicals to the flood waters and suspended sediments during and after the flood, while large installations like chemical plants only give problems near the dike breach where high flow velocities prevail. The simulated concentrations of toxic substances frequently exceeded legal threshold levels

Keywords: flooding, environment, river delta management, dike breach, pollution

1. INTRODUCTION

So far, little research has been carried out into the environmental impacts of floods (Zwolsman et al., 2000). Some drastic consequences of flooding such as waterborne diseases or contamination of agricultural lands are difficult to express in monetary terms (Albering et al., 1999; Smith and Ward, 1998). In a model study, a breach of a river dike east of Rotterdam, resulting in a gap in the dike was simulated to assess the possible environmental consequences of the release of pollutants during the induced, major flooding event. In the low-lying western part of The Netherlands, the most disastrous floods are expected to occur during periods of high river discharge, as a result of dike failure along some river section south of Rotterdam. Supply of water to these locations by the river Rhine is large and the difference in water levels during periods of high discharge is large: design water levels of the river that are used for the design (heights) of river dikes may be 9 m higher than the adjacent polder areas that must be protected by the dikes. Failure of the river dike is not simulated; a 250 m wide gap is assumed to develop instantaneously and to be closed 10 days later. The conceptual framework that was established for the sequence of events during a flood is depicted in Figure 1. A dike breach releases water into a polder district. The location of the gap is such that the discharge capacity of the river branches near the gap do not pose significant limitations with respect to the inflow rate. During the flooding event, the ratio between the out-of bank flow volume ($1500\text{ m}^3\cdot\text{s}^{-1}$ on average) and the in-bank flow volume is approximately 15%. The scour of the water flow and/or the high water level causes damage to *source objects* (constructions, homes, industrial complexes and farms). The damaged source objects may fail and subsequently release chemicals and micro-organisms into the water. The volumes of pollutants that are released from the source objects are estimated. Pollutants are dispersed through the air (not included in this study), dissolved in water and adsorbed to suspended matter. The release, migration, decay and sedimentation of the pollutants is simulated with flow- and sedimentation models. The polluted water and suspended matter affect people and ecosystems -the *targets* - in the flooded districts. Finally, an assessment is made of the environmental damage, expressed in monetary terms.

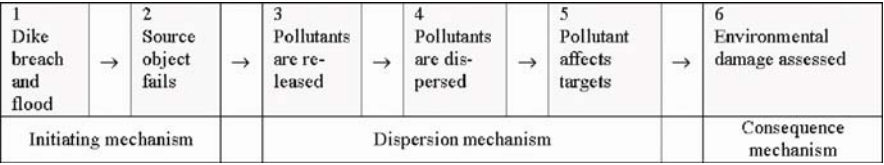


Figure 1. Sequence of events in a chain reaction after a river dike breach

2. THE 'KRIMPEN' CASE STUDY

In the study, attention was focused on the immediate and longer-term effects of chemicals released, dispersed and/or deposited. A river dike breach near the city of *Krimpen aan de Lek*, east of Rotterdam was the starting point. To investigate the fate of released pollutants and suspended sediments, a flooding model and a water quality model were integrated. The modelling period was ten days, after which an area of 46,645 ha was flooded. This area was considered for the environmental assessment. The step time of the model was 15 min. The flood covers parts of Rotterdam and smaller cities like Delft, Zoetermeer and Gouda, cf. Figure 2. The land surface elevation in the area ranges from 1.5 to 6.5 meters *below* mean sea level (M.S.L.). The greater part of the flooded area (70%) is grassland with a clayey topsoil, the deepest parts of the area are peaty soils; there are many residential areas cf. Figure 3.

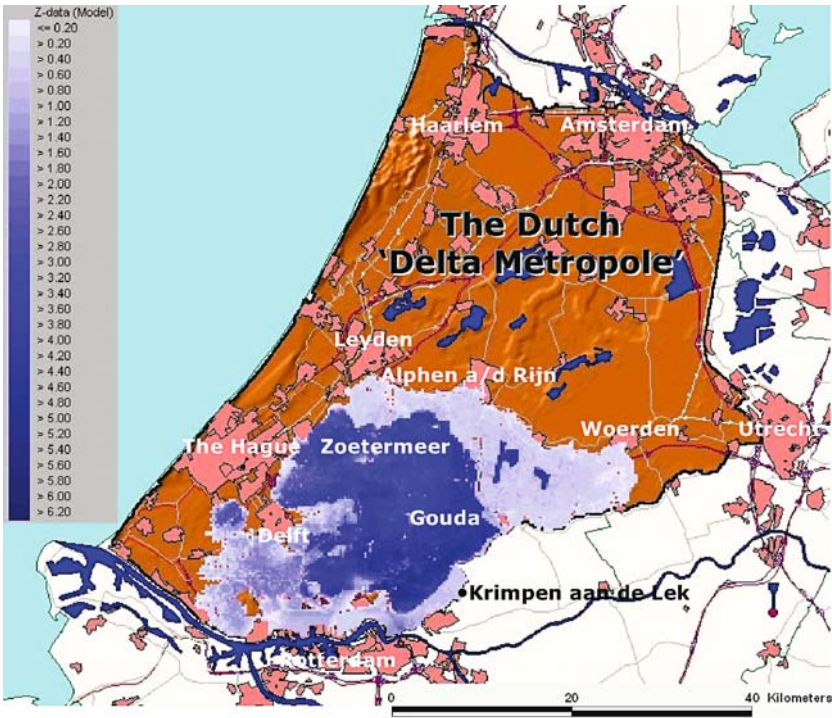


Figure 2. Gross view of the flooded area (46645 ha) and flooding depth (m), ten days after a dike breach of a Rhine tributary near Krimpen aan de Lek, located east of Rotterdam. The flooded area covers the southern part of the highlighted Dutch 'Delta Metropole', the most densely populated region of The Netherlands. Polder depth below MSL has a profound impact on the flooding depth

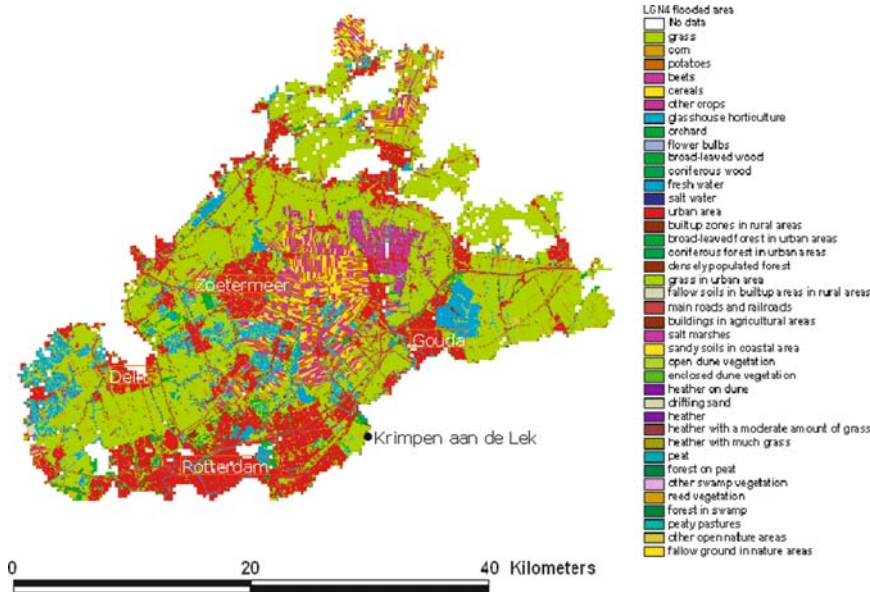


Figure 3. Land use at the flooded area after a dike breach near Krimpen aan de Lek

2.1. The Hydrodynamic Sobek Model ‘Delft1D-2D’

Flooding was simulated with the model ‘Sobek’ of WL|Delft Hydraulics (Dhondia and Stelling, 2004). Its *Overland Flow* module consists of a 2D modelling system based on the Navier-Stokes equations for free surface flow. Sobek also handles 1D elements like (small) water courses and hydraulic structures. In this 1D-2D combination, overland flow, including embankments and natural levees, is simulated through the 2D equations of Sobek *Overland Flow*, while gullies and the hydraulic structures are modelled with Sobek 1D *Channel Flow*. Both modules produce finite difference equations that are linked through an implicit formulation for joint continuity equations at locations where both modelling systems have common water level points, cf. Figure 4.

The modelling period of the flooding event was ten days and the time step of the model 5 minutes. The land use data, required to assess flood damage in rural areas, were retrieved from the LGN4¹ land use database of Alterra and has a resolution of

¹ The LGN database is a geographical database that describes the land use in The Netherlands. The database uses a grid structure with a cell size of 25 meter, the scale is about 1:50,000. The nomenclature of the LGN4 database contains 39 classes covering urban areas, water, forest, various agricultural crops and ecological classes. LGN is created for an important part on the base of satellite imagery, but also other data is integrated into the database. Currently 4 versions exist LGN1 - LGN4 which span a time period of 1986 to 2000. The production of the LGN5 database started in January 2004. The LGN5 database is based upon satellite images of 2003 and 2004. The LGN5 database is available for the entire Netherlands since mid-2005 (www.lgn.nl).

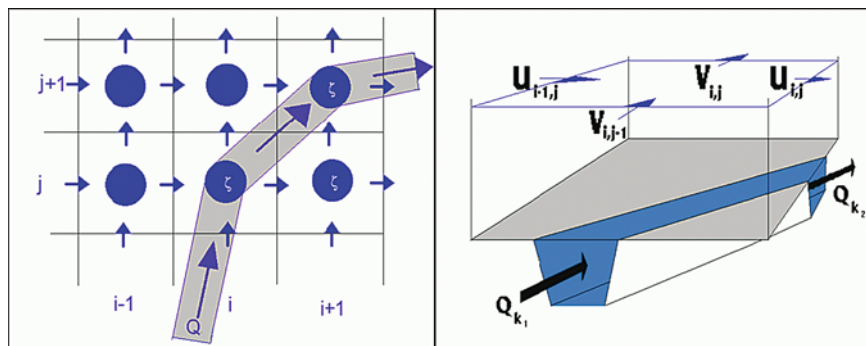


Figure 4. Schematisation of the hydraulic model Sobek: combined 1D/2D grid (left); combined continuity equation for 1D2D computations (right). Source: Dhondia and Stelling (2004)

25 × 25 m square grid cells. The results of the Delft1D2D-model consist of a digital elevation model of the study area and maps of water depths and flow velocities with time. All data were relocated geographically to model cells of an imaginary, regular 250 × 250 m grid, which was used in the simulation tools and superimposed on the flooded area. The maps, containing water depths and flow velocities were provided as a series of time steps with a six-hour time interval.

2.2. The Water Quality Module 'Delwaq'

The water quality module 'Delwaq' of WL|Delft Hydraulics simulates the fate of pollutants following the flooding event, simulated by Sobek 1D-2D. Grid cells were involved in the water quality simulations only if the height of the flooding waters exceeded 0.2 m. An exception to this criterion was made for fertilizers. The vast majority of fertilizers in the flooded area is found on land used for agriculture. Phosphates from this source will dissolve in the water flooding the farmland. Even a very thin layer of water will suffice to do so. Also the liquid part of manure present on farms (assumed 50% of the total), will be easily transported by flowing water. Therefore, a threshold value of 0.02 m of water was chosen for the release of phosphates. Release of phosphate from other sources was not modelled in this study.

The potential sources of contamination are quite diverse: industries, garbage dumps, farms (herbicides, pesticides), cars, oil tanks near petrol stations, diffuse sources of contamination in the soil and, not in the least, the water of the river Rhine which inundates the polder district. In this project, a simplified version of Delwaq was adopted, describing the release and migration of pollutants with a limited set of parameters, either dissolved or suspended. The following simplifying assumptions were made (Stuyt et al., 2003):-

- Toxic substances are stored in various types of containers in-, and outside buildings, in the soil and in cars; parameter C_s ($\text{g} \cdot \text{m}^{-2}$);
- two criteria for the release of toxic substances into the flooding waters were used, labeled 'v' and 'h':

- *v*: *high flow condition*: release will occur once the water *velocity* $v > 2 \text{ m/s}$, provided that a certain water height is present (set at 0.5 m). The high flow condition represents collapse of a structure or vital parts of a storage container or the turnover of a car. This high-energy condition will generally result in an (almost) instantaneous release of toxic substances, hence the (first order) release constant K_2 is set to a release of the complete contents of a container in an hour, i.e. $K_2 = 1 \text{ h}^{-1}$ ($= 24 \text{ d}^{-1}$), regardless of the size of the container;
- *h*: *high water depth condition*: release will occur once the water *height* $h > 1 \text{ m}$. A water height in excess of one meter will result in a relatively gentle release of toxic substances, e.g. as a result of slow dissolution or collisions of floating debris with containers. Therefore a slower release rate of half the contents of a container during 24 hours is assumed, i.e. $K_2 = \frac{1}{48} \text{ h}^{-1}$ ($= 0.5 \text{ d}^{-1}$), regardless of the size of the container;
- the values of *v* and *h* were chosen on the basis of expert judgement in consultation with TNO Building and Construction Research, who have considerable experience with calculations of strength of buildings and other constructions; no sensitivity analysis was made to investigate their impact on the results;
- the release of toxic materials can be modelled as a constant flux until depletion (parameter K_1 ($\text{g/m}^2 \cdot \text{s}$)) or as a flux which decreases proportionally with the decreasing supply of contaminant at the source (parameter K_2 (day^{-1})). In this study, the latter, a first order process, option was selected because it was considered the most likely (expert judgement);
- substances, dissolved in water (C_w) ($\text{g} \cdot \text{m}^{-3}$) are subject to transport, supply from the soil, sedimentation and decay;
- dissolved or suspended pollutants may decay with time, e.g. through evaporation, bacterial degradation, chemical reactions or combinations of these; the decay is simulated as a first order process;
- the decay of contaminants in soils is not included in the modelling concept as the 10-day modelling period is very short as compared to typical decay rates in soils.

2.3. The ‘ERA’ Sediment Transport Model

Suspended material is a crucial transport medium for pollutants since key pollutants like heavy metals and insecticides are easily adsorbed to (moving) soil particles. The accumulation and spatial distribution of hazardous toxics is therefore linked to suspension- and sedimentation processes. When a dike breach occurs, riverine silt- and clay sized material enters the area. At high flow velocities, erosion may further enhance the concentration of suspended solids in the water; potential sources are channels/depressions and bare arable land. The ‘ERA’ sediment transport model that was used in this study was primarily developed to simulate sediment accumulation in so-called Emergency Retention Areas (‘ERAs’) in The Netherlands (Asselman, 2003; Cuypers, 2000). The modelling assumptions are:

- stocks of substances in soils (C_s) may increase by sedimentation and decrease due to resuspension;

- sedimentation of suspended matter occurs at flow velocities <0.5 m/s, using the approach of [Chen \(1975\)](#);
- the settling velocity of suspended sediment is fixed on $7 \cdot 10^{-5}$ m/s, i.e. a value for silt particles ([Asselman, 2003](#));
- the highest suspended sediment concentration in the Rhine and Meuse rivers usually occurs just prior to the peak discharge of the river ([Middelkoop, 1997](#); [Middelkoop and Asselman, 1998](#)) yet the sediment load of the river is assumed constant during the 10-day flooding event, i.e. 0.284 kg/m^3 ; this average figure is derived from various concentrations recorded during historical peak discharges at or near $16,000 \text{ m}^3 \cdot \text{s}^{-1}$ of the Rhine at the German-Dutch border town Lobith, located 120 km east of the dike failure ([Asselman, 2003](#)); erosion near the dike breach is not taken into account.

The transport of suspended solids was simulated with both the Delwaq and the ERA models.

2.4. Compounds and Physical Mechanisms

For all toxic substances in the flooded area, sources, volumes, release rates and sedimentation mechanisms were investigated. The release mechanisms depend on the flooding conditions and the way the materials are used or stored. Ten groups of harmful compounds that were regarded the most relevant for this case study were included in the simulations, cf. Table II. The selection was partly based on a combination of 'toxicity' and volumes present, and partly on known flood cases elsewhere ([Gautam and Van Der Hoek, 2003](#)). Toxicity should be interpreted somewhat loosely as 'the capacity to alter or disturb the receiving environment', hence phosphates - fertilising the soil of rural areas - were included. Decay rates are derived from [Suarez and Rifai \(1999\)](#). Sedimentation essentially takes place because of adsorption to particles. From adsorption-desorption processes an 'average' time fraction was estimated during which a component is adsorbed. This time fraction varied from 0.9 for strongly adsorbed material to 0.5 for the weakest adsorbents. For modelling purposes a minimum value for v for the release of material was required that was in excess of the sedimentation threshold velocity. To have any material released during the 'high water depth' condition a somewhat lower sedimentation threshold was chosen for the 'h' condition than for the 'v' condition.

2.5. Locations and Quantities of Pollutants

Data on locations and stocked quantities of potential pollutants were acquired for industrial sites, farms and cars. These data were converted to figures, associated with the constituting chemical compounds, listed in Table II ([Stuyt et al., 2003](#)). Data associated with industrial sites were retrieved from the Dutch 'UBI'-list² which includes all industrial activities that are potentially polluting for soils, including

² See <http://www.ubi-model.nl>

Table 1. Compounds and associated parameters used in the 'Krimpen' case simulations

Release/ sedimentation code	Compound	Release criteria (threshold) for most industrial sites	Release rate	Decay rate	Sedimentation rate	Sedimentation threshold	concentration in Rhine water	
		v(m/s)	h(m)	K ₂ (1/d)	C ₃ (1/d)	V _{sed} (m/d)	v(m/s)	(mg/l)
1	Suspended sediment			0.0	0	6.048	0.5	284
2v	Mono aromatics (BTEx)	2	0.5	24	0.00864	0		0.000209
2h			1	0.5	0.00864	0		
3h	Micro-organisms		1	0.1	–3,4	0		–
4v	Poly Aromatic Hydrocarbons – PAH	2	0.5	24	0	4.234	0.5	0.055072
4h	(sum PAH, naphthalene)	0.25	1	0.5	0	4.234	0.2	
5v	Persistent Organic Pollutants –	2	0.5	24	0	5.443	0.5	0.00589
5h	POP (DDT, PCB, Dioxin)	0.25	1	0.5	0	5.443	0.2	
6v	Alkanes (straight, cyclo)+ alkenes	0.25	0.5	24	0.000864	5.443	0.5	0.1278
6h			1	0.5	0.000864	5.443	0.2	
7v	Dense Non-aqueous Phase	2	0.5	24	0.00864	0		0.000266
7h	Liquids DNAPL (TRI, PER)		1	0.5	0.00864	0		
8v	Heavy metals	2	0.5	24	0	4.234	0.5 or 0.2	0.163706
8h		0.25	1	24	0	4.234	0.5 or 0.2	0.000588
9v	Nutrients (phosphate)	2	0.5	24	0	3.024	0.5	0.825317
9h			0.02	0.5	0	3.024	0.2	
10v	Pesticides	2	0.5	24	0.000086	0		
10h			1	0.5	0.000086	0		–

probabilities that the pollutants are released from their sources, toxicities and quantities. All 701 companies in the region with activities referred to on the UBI-list were included in the analysis. The list includes the following categories: aluminium, batteries, gasoline, oil, pharmaceutical raw materials, pharmaceutical industry and wholesale, colouring agents, fertilizer, synthetic materials, synthetic materials processing plants, raw materials for foodstuffs, margarine, oil and fat (industry), petrochemical industry, plastics processing industry, polishing materials, steel cables and wires (plants), petrol stations, paints, detergents, cosmetics, wire, flour, steel components (plants), rubber articles, cleaning agents, slaughter devices, illumination devices (plants), meats and meat products, recycling, waste paper, industrial cleaning, litter, glue, lubrication oil and grease, electric transformers, self-adhesive materials, paraffin oil, fuels, car paints, coating, yacht painting and maintenance, spraying and electrolytic coating, ship maintenance and cleaning, slaughterhouses, chemical industry (raw materials), print shops and dry cleaning.

The following sources of pollution in urban areas were included: households, cars, motorcycles, petrol stations, printers, dry cleaners and offices. Data on farms, located in the area were supplied by the Dutch National Institute for Agricultural Economics. Included are fertilizer-P; paraffin-oil, Diesel oil and fuel oil (as one category); farmland manure-P and insecticides, fungicides, herbicides and nematocides (as one category). The quantities of pollutants, found in the Rhine (cf. Table II) were used during modelling as well.

2.6. Release of Pollutants into the Environment

Release criteria have been determined for a total of 50 pollutants (Stuyt et al., 2003); Table II contains the release criteria for a selection. The figures indicate the weight percentages of pollutants released once the release thresholds, given in Table II, are met. Usually 50% of a toxic compound (100% for heavy metals) will be released, regardless the criterion. All percentages are assigned on the basis of expert judgment; reliable data were not available. For large storage tanks in the petrochemical industry containing large amounts of oil products, and for petrol stations with underground storage tanks, it was assumed that only velocities in excess of 2 m/s may cause sufficient damage to containers. For cars, the release of lubrication oil and petrol is expected to occur once the 'v' or 'h' criterion is met. However, if only the – less severe – 'h' condition is met, 10% if the oil and petrol is expected to be released, instead of the 50%, stated for the 'v'-condition.

Fuel oil, phosphates and pesticides found at farms will be released following the mechanisms and criteria shown in Table II. Pesticides are stored in barns, mostly well protected against scour due to high velocity water flow, hence failure of bags and containers is associated with water table height ('h' criterion). Oils are kept in tanks that are assumed to fail only at high flow rates. Phosphates and the liquid part of manure will be dissolved and transported easily by waters flooding the farmland, hence a 0.02 m threshold value was chosen for the release of phosphates. The release of phosphates from other sources was not simulated in this study.

Table 2. Some examples of the percentages of pollutants that will be released, once the release criteria are met

Category	Mono aromatics	Micro-organisms	PAHs	POPs (DDT, PCB, Dioxine)	Alkanes (straight, cyclo)+ alkenes	DNAPLs	Heavy metals (zinc (a) and cadmium (b))	Phosphate	Pesticides									
	2h	2v	3h	4h	4v	5h	5v	6h	6v	7h	7v	8h	8h	8v	9h	9v	10h	10v
release criterion during the flood – see Table 1																		
Batteries																		
Gasoline and oil		50		50		50			50				50					
Paints	50									50		100						
Wire										50								
Industrial cleaning																		
Lubrication oil and grease	50			50				50				50						
Paraffin oil		50			50		50		50				50					
Chemical industry (raw materials)	50			50						50		100				50		
Large industries- 'Seveso II' (Seveso II, 1996)	50	50	50	50		50	50	50	50	50	50		100			50	50	50
cars (located in built-up areas and on motor-ways)	10	50		10	50	10	50	10	50			10	50					
Fuel oils, fertilizers and pesticides on/near farms in rural areas		50			50				50					50	25		25	
Farmyard manure, applied on arable lands															50			

Table 3. Release criteria for compounds, stored at farms and rural areas

Compound	h>1 m % released	h> .02 m % released	v>2 m/s % released
Phosphates		50	
Oils (3 types)	–		50
Farmyard manure (P)	50	50	–
Pesticides	25		

3. RESULTS

The maximum extent of the inundated area was 654 km², storing 1.37*10⁹ m³ of water. The 'h' criterion was exceeded in a very large area, and is responsible for the releases of most pollutants. The 'v' criterion was reached in a small area near the dike breach only.

3.1. Suspended Particles

Both the Sediment Transport Model ERA and the Water Quality Module Delwaq were used to simulate transport and sedimentation of suspended particles. The ERA model takes into account the material transported into the area with Rhine water (Asselman, 2003) whereas the Delwaq model also includes land-sourced material. Given 0.284 kg/m³ of suspended material in the river, approximately 388*10⁶ kg of sediment (i.e. a uniform sediment layer of 0.35 mm) was deposited in the flooded area ($\rho_{\text{sediment}} \approx 1,700 \text{ kg/m}^3$). Following the ERA-model, 22% of the total sedimentation (in terms of weight) took place during inundation; 73% is deposited during the settling stage. In the lower parts of the area, sedimentation during the settling stage amounts up to 1.2 kg/m², elsewhere in this peaty area between 0.5 and 1 kg/m² and in the remainder of the area between zero and 0.5 kg/m². Soil material that was washed away from the cavity beyond the dike breach accounted for 5% of the total suspended sediment.

The sedimentation pattern is depicted in Figures 5 and 6. The area around the dike breach shows a concentric zone where no deposition occurs because of high stream velocities. Up to 6 kilometers from the dike breach, the layer thickness varies between 2–8 mm, in the lower parts of the area from 0.4–2 mm, elsewhere <0.4 mm.

3.2. Mono-Aromatics

In Figures 7 and 8, concentrations of dissolved mono-aromatics are shown. The highest concentrations are found near the downstream borders of the flooded area. Most aromatics originate from the river Rhine. Less than 10% of all simulated mono-aromatics will be benzene. Still, the flooding will lead to concentrations well in excess of the Dutch Intervention value (0.03 mg benzene /l), even after 10 days. Hence a substantial part of the inundated area will be covered with

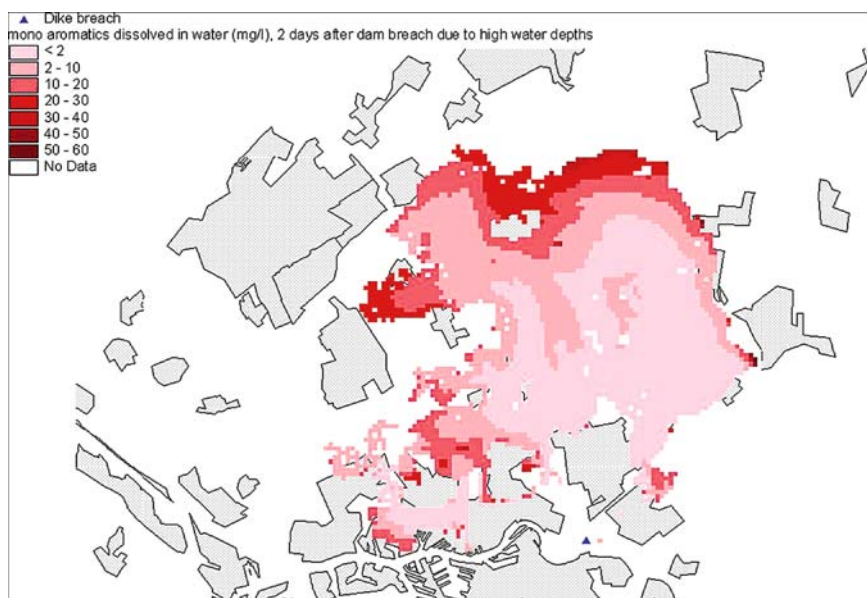


Figure 7. Mono-aromatic concentrations, released following the 'h'-criterion, 2 days after the dike breach

seriously contaminated water for more than 10 days. Due to decay, the concentrations will gradually decrease to values that won't pose any risk to human health.

It is important to realise that, during the simulations, the solubility of compounds in water may be exceeded temporarily. For instance, immediately after collapse of a storage tank, large volumes of contaminants are released. This may be a layer of oil, floating on the water, or a DNAPL layer moving over the ground surface. This type of contamination, which is not included in the current versions of the models, may be a major threat to flora, fauna and humans, or result in pollution of (underground) piping systems like those used for municipal drinking water, which is difficult to remove.

3.3. PAHs

PAHs will adsorb to and settle with suspended sediment. The deposition PAHs as simulated with the Delwaq model is shown in Figures 9 and 10. PAHs, imported with the incoming Rhine water are responsible for the bulk of the contamination. Erosion of (contaminated) particles within the flooded area with the Delwaq model was severely underestimated due to conceptual shortcomings of this model: erosion from areas with water heights in excess of 1 m will only be simulated for flow velocities exceeding 0.25 m/s. This means that many toxic substances will not be released

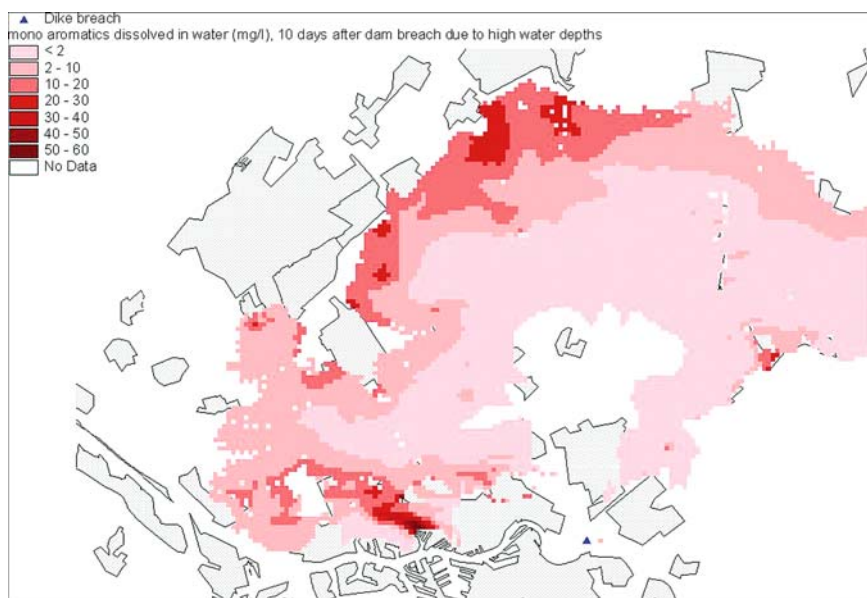


Figure 8. Mono-aromatic concentrations, released following the 'h'-criterion, 10 days after the dike breach

into the environment, despite water heights exceeding 1 m. This shortcoming of Delwaq resulted in an underestimation of the release of land based material, which can be easily observed in Figure 9 which only shows material that was simulated to be released relatively close to the dike breach. It can be expected that PAHs (and other substances) will be deposited further away from the dike breach as well. The contamination levels of the sediment slightly exceed the Dutch intervention value for PAK10, i.e. 40 mg/kg dry matter for a 'standard' soil. Figure 10 clearly illustrates that a significant land-based source of PAHs is formed by cars: motorways can clearly be identified.

3.4. Alkanes and Alkenes

Maximum predicted deposits for alkanes are 6 g/m^2 . The contamination appears to be dominated by riverine sources. With 2 kg of deposit per m^2 of flooded area, the contamination is 3 g per kg of sediment. As a reference for a contamination assessment, component mineral oil is the most suitable; 3 g per kg of sediment lies between the Dutch Target- and Intervention values for mineral oil, i.e. $0.05\text{--}5 \text{ g per kg}$. Conceptual limitations of Delwaq, as outlined for PAHs, also apply to alkanes; hence only alkenes, located relatively close to the dike breach are released into the environment.

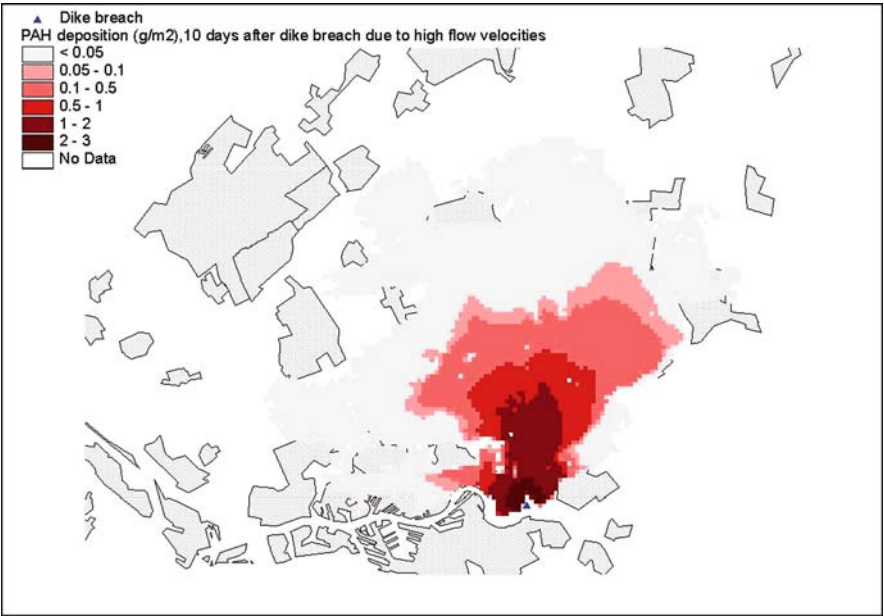


Figure 9. Concentrations of PAHs, released following the 'v'-criterion, 10 days after the dike breach

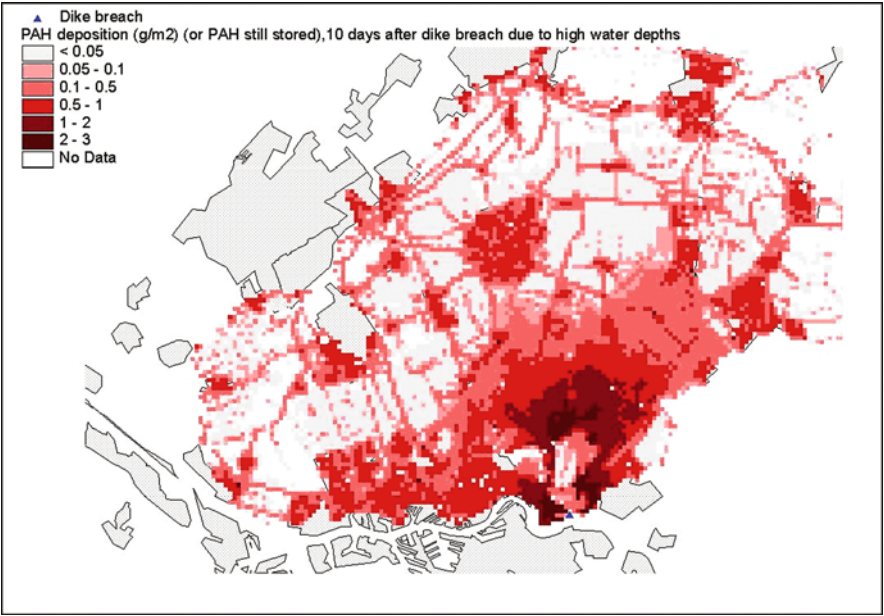


Figure 10. PAHs present after 10 days, either deposited after release subject to the 'h' criterion, or as unreleased source

3.5. DNAPLs

In line with other non-adsorbing components, accumulation of DNAPLs takes place near the downstream borders of the flooded area. Most typical examples of DNAPLs are Per (chloro-ethene) and Tri (chloro-ethene) with Dutch intervention values of 0.04 and 0.4 mg/l respectively. These values will be exceeded in a large area for several days, particularly those of Per. While natural decay is likely to reduce the concentration to sub-toxic values, DNAPLs may accumulate as a separate phase since they are denser than water. They may even percolate into the ground, causing soil contamination that may last well beyond the flooding event.

3.6. Pesticides and Herbicides

In the simulations, pesticides are released at high water levels only. Concentrations of pesticides, 2 and 10 days after the dike breach are shown in Figures 11 and 12. A local rise in concentration to maximum values of 3 mg/l is caused by companies with stocks of pesticides which are located further away from the breach. Pesticides are being modelled as one single group yet in fact this group consists of many agents with various decay rates and ecological risks. Concentrations above 0.1 mg/l - the maximum allowed for drinking water - always causes an ecological risk, but concentrations as low as 0.01 $\mu\text{g/l}$ may be toxic. Hence, it was established that

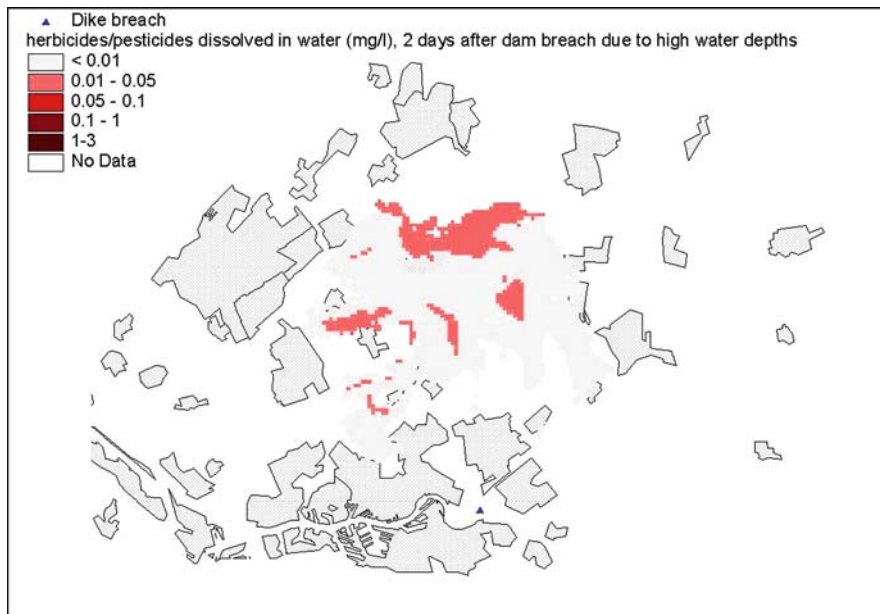


Figure 11. Concentrations of pesticides, released following the 'h'-criterion, 2 days after the dike breach

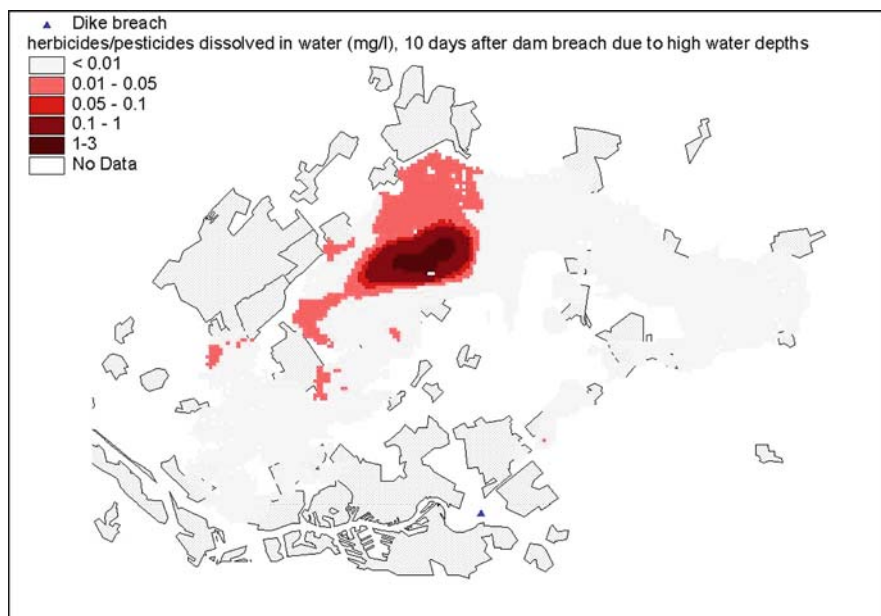


Figure 12. Concentrations of pesticides, released following the 'h'-criterion, 10 days after the dike breach

concentrations of herbicides and pesticides may cause a substantial risk, particularly because the grid-size of the model is 250×250 m, so that in reality, concentrations may be much higher. Conversely, due to decay, the concentrations will decrease substantially with time.

The deposition is mainly caused by phosphates entering the area with the river water. In reality, many more phosphates will be released from manure, applied on arable land than the model output suggests. However, due to the problems with Delwaq with respect to the simulation of the erosion of adsorbed substances, the simulated release of these phosphates is substantially underestimated. Indeed, the release criterion $v = 0.25$ m/s is only met in a limited area. Despite all this, the deposition of P is quite high, with values up to 250 kg/ha . It is Dutch policy to tolerate a phosphate surplus of $20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ at the highest (the so-called MINAS legislation).

3.7. Heavy Metals

Both the ERA and the Delwaq models were used to calculate concentrations of heavy metals, deposited during the flood. The results of the ERA-model are discussed here. They suggest that the dominant source for Zn contaminations is the incoming Rhine water. Near the breach, maximum deposition values are predicted around 7 g/m^2 . In this area, 10 kg/m^2 sediment is deposited, hence the contamination level is about

700 mg/kg sediment. The Dutch Target and Intervention values for Zn are 140 and 720 mg/kg dry matter, respectively, hence the incoming Rhine water may give rise to substantial Zn contamination. For Cd, maximum deposition values amount to 2.5 mg/kg sediment, causing moderate Cd contamination, given the Target and Intervention values which are 0.8 and 25 mg per kg of soil material, respectively.

4. ASSESSMENT OF DAMAGE FROM THE ENVIRONMENTAL IMPACTS

The results of the simulations show that the flood waters contain amounts of benzene, PER (DNAPL) and pesticides well in excess of Dutch Intervention values. These compounds accumulate at the borders of the flooded area. Clearly, one should be careful with the intake of surface water for drinking purposes during this time. As long as the flood lasts (this depends on the capacity to pump the waters out of the polders, in this case approximately 60 days), most components are likely to decay naturally to sub toxic levels. Simultaneously, growth of algae is likely, causing oxygen depletion and growth of toxic organisms like blue algae. The deposition of polluted sediment may cause health risks and adverse effects on ecosystems. Therefore, contact with polluted sediment could have some adverse health effects, particularly if there is a risk of intake. According to Van Bruggen et al. (1995) the most important routes of contact are skin-hand-mouth contact, polluted drinking water, wind dispersion and consumption of crops and dairy products from cattle, raised on polluted pastures.

The possible reduction of the land use potential for agriculture due to Cd- and Zn-contamination is assessed using the Dutch 'LAC-alert values'. These are presented in Table 4, together with average loads in suspended Rhine sediment. For arable land, these loads exceed the LAC-alert values; for pasture, only Zn exceeds the value. Regular agricultural activities during which top layers of soil are mixed, may eliminate possible risks in arable and pasture land because the contamination is reduced to values below LAC-values.

The above observations are based on a simple model, using global soil characteristics, just a few chemical compounds and only considering the river Rhine as a source of pollution. Local variations in soil characteristics, variation of concentrations in suspended river sediment and the proper inclusion of a wider range of

Table 4. LAC-alert values [mg/kg sediment] for arable land and pasture on clay soil and the quality of suspended sediment in the Rhine (1992–2000)

Compound	Loads in suspended material in the Rhine (mg/kg)	LAC alert values (mg/kg)	
		Arable land	Pasture (cattle)
Cd	1,8	0,5	3
Zn	467	350	350

chemicals from land sources in the flooded area may lead to higher estimates of contamination of the soil, and associated greater health risks.

4.1. Clean-up Costs

According to Dutch law, all soil contamination induced after 1987 must be removed. In the flooded area, 15% is urban area and 85% is agricultural land. The average deposited layers of contaminated sediment will be a few mm thick only. In most agricultural lands removal of such material will be difficult if not impossible. Most likely, the sediment will be mixed with the subsoil whereby the contamination level will decrease. Concentrations of contaminants in the mixed topsoil were calculated for arable land and pasture. Average background concentrations of Zn and Cd in the subsoil are 97 and 0.4 mg/kg respectively (Van Dijk et al., 1998). Given the maximum deposition values for Zn and Cd, their concentrations in arable land increased, due to the flood, with 20%; in pasture land the concentrations will be doubled, cf. Figures 13 and 14.

In urban areas, contaminated sediment may be collected from hard-covered areas and disposed of as chemical waste. A realistic cost assessment could be that merely 30% of the sedimented area (15% urban and 15% rural) would be disposed of as polluted soil. Assuming soil remediation costs of €90/m³ (a rough estimate) the cleanup costs for the region would be €80M.

Before such a cleanup is undertaken, detailed soil analyses should be carried out, following a risk analysis currently used in soil contamination problems. In such

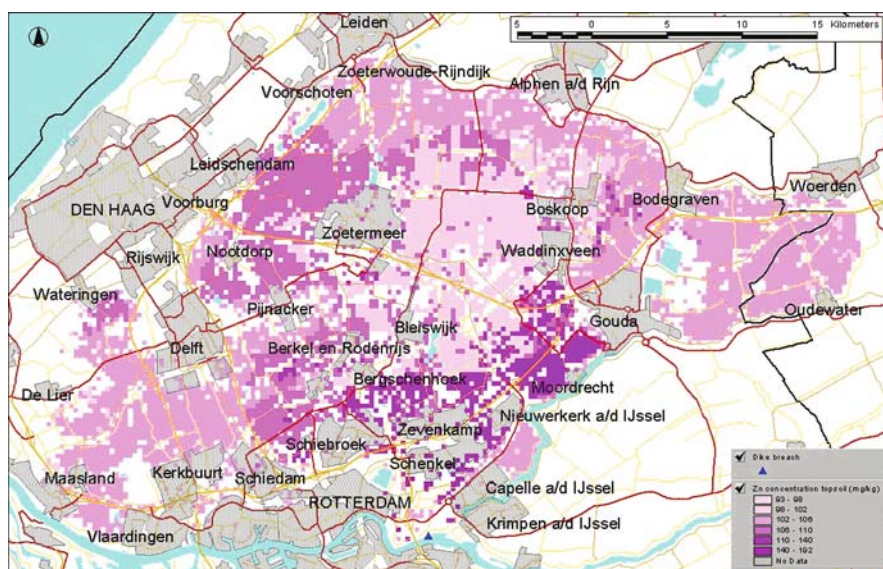


Figure 13. Zn-concentrations after mixing with the topsoil [mg/kg], as calculated with the ERA model

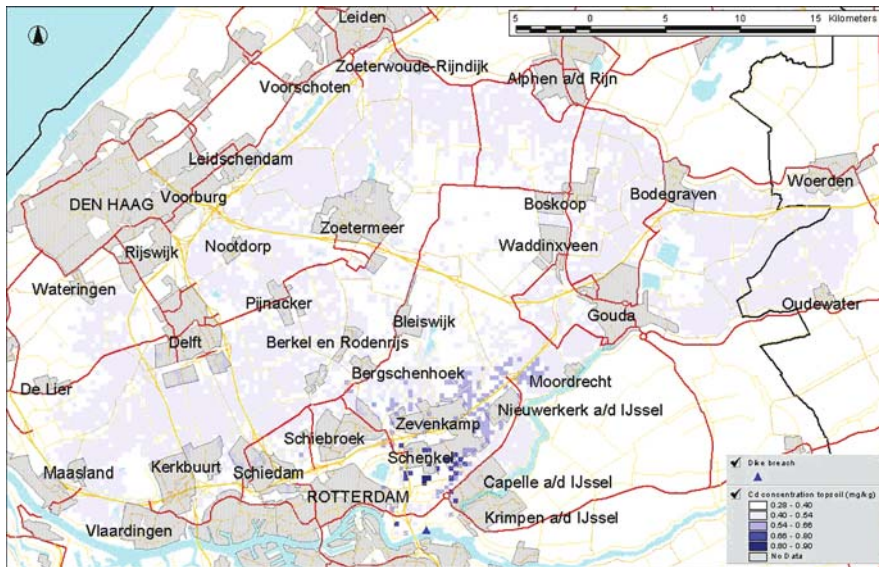


Figure 14. Cd-concentrations after mixing with the topsoil [mg/kg], as calculated with the ERA model

an analysis, soil pollution is divided in three different risk categories: immediate humane risks, immediate ecological risks and risks of spreading of contamination; the latter leading to risks in the longer term. In the regulations, these risks are linked to the urgency of clean-up. After the risk analysis, clean-up costs can be calculated for the locations where an immediate risk exists. In addition, an overview will be made of the consequences for those areas where contamination is not removed. Possible consequences are loss of live, loss of multi-functionality of land, loss of ecological values, drinking water problems and more. The latter analyses were beyond the scope of this project.

4.2. Damage in Agriculture

Flood damage due to excessive precipitation in The Netherlands in 1998 was estimated to € 427 M, 85% of which had occurred in agriculture. Van der Most and Van der Bolt (1999) have developed a protocol to quantify crop damage. The following land use categories were investigated: grassland, arable land, high-grade agriculture, horticulture and greenhouse agriculture. Flooding damage on agricultural fields is related to inundation, deterioration of soil structure and high salt concentrations of flooding waters. For three groups of crops and for seven soil types, Van der Bolt and Kok (2000) have modelled this type of damage due to short, extreme precipitation events, both on arable land and on grassland. When extremely shallow groundwater tables develop on arable land, damage to crops is maximum after 72 hours of continuous ponding.

Table 5. Estimated maximum crop damage in agriculture

Crop	Area		Average inundation (m)	Produce (€/ha)	Damage (M€)
	(ha)	(%)			
grassland	36 094	71.4	1.75	900	32
glasshouse horticulture	3 494	6.9	2.35	225 000	786
cereals	2 394	4.7	3.32	900	21
potato (edible)	2 006	4.0	3.41	4 500	9
maize	1 413	2.8	2.14	900	1
sugar beets	1 144	2.3	3.30	2 800	3
orchard	100	0.2	2.92	11 500	1

In addition, an assessment was made of the damage that is the result of reduced trafficability and soil tillage. As data for arable land were unavailable, damage parameters for arable land were based upon damage calculated for grassland on sandy soil (Postma, 1992). The parameter values have been corrected for soil types other than sand and for crops other than grass. The flood damage functions for grass-, and arable land contain coefficients that are seasonally dependent. As a result, inundation of grassland during the winter season will not induce any damage.

The calculated damages appear to be realistic yet cannot be verified due to a lack of data. In Van der Bolt and Kok (2000), flood damage to crops was assessed by multiplying flooded areas with average crop yields, the produce of which ranging from €900/ha (cereals) to €30, 000/ha (flower bulbs). In glasshouse horticulture, flooding damage reaches a maximum at 0.5 m inundation depth (Van der Bolt and Kok, 2000). For flooding events less than 72 hours, the damage is assessed to be 50%; for longer periods 100%. Yield losses range from €185, 000/ha for vegetables to €275, 000/ha for pot- and bed-plants.

For the case 'Krimpen', inundation data is specified for the major categories of crops in Table 5. Assuming that crop damage is 100% after 72 hours continuous inundation, which is the case at all agricultural fields in this simulation, the damage was calculated by multiplying the produce (€/ha) with the associated acreage (ha), yielding a total damage due to flooding of M€853, assuming that the farmers can work their lands again the next year.

5. CONCLUSIONS

The results of this study are of preliminary nature as the innovative simulation tools that were used need further improvement. Also, more reliable input data need to be obtained. They nevertheless show that flooding of a densely populated area may have a considerable impact on the environment; on agriculture because of physical damage to crops and installations and due to toxic sediments on agricultural fields; on nature areas because of deposition of phosphates and toxic materials in sediments; and on humans, because of toxic concentrations of chemicals in the

floodwaters, growth of micro-organisms and algae that may cause diseases and because of the deposition of polluted sediments in sensitive areas like playgrounds and gardens. The effect of deposition of sediment is an important factor as this may cause damage to e.g. subways and sewage systems. An important finding was that numerous, apparently less relevant objects like cars may, as a group, release substantial amounts of toxic chemicals to the flood waters and suspended sediments, while large installations like chemical plants only give problems near the dike breach where high flow velocities prevail. The simulated concentrations of toxic substances locally exceeded permissible threshold levels. In conclusion, it is justified to state that the environmental impact of flooding will often be substantial. Hence, in order to be comprehensive, damage to the environment cannot be ignored in any assessment of the effects of a flooding event.

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CHAPTER 8

STRUCTURAL ECONOMIC EFFECTS OF LARGE-SCALE INUNDATION

A simulation of the Krimpen dike breakage

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Abstract: The paper's main concern is to establish a general methodology for economic loss estimation as a result of a large-scale flooding. The issue of economic loss definition is addressed in an attempt to unify the scattered definitions currently circulating in the 'disaster' literature. Total effect includes the direct loss to households and government, direct business interruption and induced indirect losses on production all over the country. The input-output model is proposed as a basic modelling framework. The discussion involves appropriate definition of direct and indirect costs within this framework. Adaptations to the model are proposed to account for asymmetric shock aspects such as 'production bottlenecks' and substitution effects. The time dimension of the model is a 2-year period. A bi-regional input-output table is utilised for tracing the inter-regional ties within the country and to estimate the disaster-induced changes of the economic structure.

The case study of a dike breakage in the province of South Holland in the Netherlands provides an example of modelling vast economic consequences. Two basic models are compared: a reference standard input-output damage evaluation model and adjusted models examining the impact of economic recovery of production 'bottlenecks' and substitution effects from imports and production transfer to other regions. It is shown that with the same level of initial disruption final loss figure depends on the ability of an economy to adjust. Whereas the presence of 'bottlenecks' in the after-flood situation drags the final estimate far below the reference figure, the emergence of flexible conditions for the economic response provides more optimistic results.

Keywords: large-scale flooding, direct and indirect economic loss, economic structure

¹ We are indebted to Christiaan Logtmeijer for computational assistance during the earlier phases of this research.

1. INTRODUCTION

Tsunamis, floods, droughts, hurricanes and earthquakes are a constant threat to society. In the past decades we observe a growing awareness of the devastating effects of these natural disasters on the economies of developing and developed countries. The World Bank, the United Nations and the European Union have published a number of reports on this problem, *inter alia* Kreimer and Arnold (2000), Freeman, Martin et al (2002), ECLAC (1991), ISDR (2002), Colombo and Vetere Arellano (2002). Parallel to this policy awareness we note a strong interest in the methodology of estimating the economic consequences of disasters on welfare and an interest in the effects of recovery plans for the economy.

In this research we are interested in the economic consequences of flooding. Specifically, we are concerned about the effects of large scale flooding in the Netherlands. Sea level rise and an increased probability of flooding of polders along the Dutch rivers ask for a quick and permanent solution. We may note, however, that there are relatively few reports on the consequences for Dutch society of *large scale flooding*. There are several publications on small-scale floodings, but there is hardly any experience with the societal and economic effects of major floods (van der Veen, Groenendijk and Mol, 2001). In the broader international literature it can also be noticed that the vast majority of academic work dealing with floods focuses on relatively small-scale disasters. This means that the authors are basically concentrating on the micro-level effects of the events, producing cost – benefit analyses for the regional level. Large-scale floodings are thus remain an uncovered issue.

However, American authors open a wider perspective on disaster analysis. They raise the issue of large-scale earthquakes, which are more characteristic for the US. Often American authors discuss the matter of natural disasters in a county-to-state scale. These are not countrywide disasters, as the country itself is big. Nevertheless the mode of analysis is very close to large-scale disaster analysis in a small country. This seems to suggest that core aspects of the methodology used in the earthquake literature can be projected for the case of a big flooding in the Netherlands.

In this paper we will report on first efforts at an empirical analysis of the structural economic consequences for the Netherlands of a dike breakage near Krimpen. The consequence of this dike breakage is a massive flooding of major parts of the Randstad.

In order to be able to deal with the economic consequences of this major flood we first need to establish an accepted definition of damage, which can be used in an economic model of the Netherlands. In Section 2 general concepts of damage are discussed and a consistent system of definitions is presented. In Section 3 the methodology we adopt to simulate a major shock to the economy is introduced, whereas in Section 4 we present the case of the Krimpen dike breakage. The data and the adaptations of a basic model for the affected area (the Province of South Holland) are set forth. We will put forward the input-output model as a basic tool. However, as we shall argue, the standard formulation needs adaptations to give it

additional flexibility to model alterations in the production system. We will also present of the results of the case-study calculations. In Section 5 we formulate our conclusions and recommendations for future research.

2. DAMAGE

Van der Veen, Groenedijk and Mol (2001) surveyed the Dutch literature on the methodology of estimating damage. It was concluded that there is no generally agreed methodology, let alone a settled definition of damage. This conclusion is due to the fact that 1) There is no agreement on the economic points of departure; financial appraisals are mixed up with cost-benefit analyses (CBA). In the latter the usual concept is economic costs, which relates to opportunity costs in welfare economics. CBA is a helpful means to weigh alternative measures against flooding, whereas a financial appraisal is often a base for investigating the sum of money to be recovered from insurance companies; 2) There is confusion on the time and spatial scales: financial appraisal limits itself to a single organisation, whereas CBA requires well-defined borders, like a nation, or the European Union; 3) Stock concepts are confused with flow concepts; 4) The borderline between direct and indirect costs is not well defined.

In the following we will concentrate on the latter two points, i.e., stocks versus flows and the demarcation between direct and indirect costs. We will do so by reviewing the international literature. Our point of departure is a national Cost-Benefit Analysis.

2.1. Basic Concepts for Damage Estimation

Twenty years ago Ellson, Milliman and Roberts (1984, p. 559) concluded on the basis of their literature survey that “most of the economic impact literature fails to make proper distinctions between the measurement of loss and the measurement of long run patterns of personal income, employment, and population growth. Much of the research has confused stock and flow concepts in the estimation of loss. Double counting is often involved, and the losses are not estimated in present value term”. Moreover, in MAFB (2000) it is stated that:

“When identifying and valuing the different streams of benefits and costs, it is helpful to think in terms of *stocks* and *flows*. It is very easy to make the mistake of including the same benefit or cost twice because of a failure to distinguish sufficiently between the stock of some asset and the flow of resources, or consumption, which that stock generates. Typically, stocks give rise to some flow of consumption or resource so that the current capital value of the stock is determined by the discounted value of the future benefits, which flow from it. In some cases the flow diminishes the value of the stock value (e.g. mining coal necessarily diminishes the stock of coal) whereas in other cases it does not (e.g. catching fish at below the rate of replacement). An appraisal can include either the stock value of a resource or the sum of all the flows that it yields but not both.”

The issue of double counting is important in assessing the value of properties. Before we start elaborating on this issue we need to find a definition of both

concepts that allows us to make an appropriate distinction between both concepts. We follow [Parker, Green and Thompson \(1987\)](#), p. 36): “*Stocks* are the capital equipment, consumer durables and other physical objects damaged or destroyed by flooding. The *flows* are the flows of national income, which would have been produced by the damaged stocks but are lost after a flood”.

The main thrust of the discussion in the literature is to assess the value of the loss. One can measure this value by either taking the stock value or the flow value. It is argued that these values, in theory, represent the same loss. So, when analysing damage that results from floodings, an assessment can be made of both the stock and the flow value of properties. Of course, this is especially relevant in the manufacturing sector.

As a result, in [Parker, Green and Thompson \(1987\)](#), p. 35–37) there is a demarcation between direct costs and primary and secondary indirect costs along this differentiation: *Direct costs* relate to loss of land, capital and machinery, thus to stocks, and primary *indirect costs* to business interruption, a flow. Moreover, secondary indirect effects relate to multipliers in the economy. The authors warn us that it is not allowed to add the first two categories (i.e. direct and primary indirect costs) unless production is lost to foreign countries.

Rose (2002) argues along similar lines. The stock of capital and machinery gives rise to a flow of production and income in the future, which means that business interruptions and capital stock affected measure the same thing. He consequently defines business interruption as a direct cost instead of an indirect one. [Rose \(2002, p. 2\)](#) states that, for several reasons, an estimate based on flows may result in a better estimate than estimating damage based on stocks, or property damage. His reasons are the following: 1) An estimate based on flows makes up a better proxy of the lost value since it also accounts for damage due to business disruptions; 2) Flow measures are more compatible with macro-economic parameters; with respect to this Rose states that a stock based concept may result in an over-exaggeration of damage since only a portion of the property value may translate into service flows in any time; 3) Estimates based on a flow concept are more compatible and more consistent with the distinction between direct and indirect damage; 4) Flow measures have an explicit time dimension, which makes modelling better to do. [Cochrane \(1997b\)](#) extends the definition of direct costs by not only including the physical damage to land, plants and houses, but also induced physical effects, which are the consequence of the disaster.

Finally, in the flooding literature there is a long lasting tradition to include also non-monetary impacts on households ([MAFF 2000](#)). To households, impacts of flooding such as increased stress, health damage and loss of memorabilia can be far more important than the direct material damage to homes and their content. Also, there are approaches to include recreational and environmental benefits in flood and coastal defence schemes. In a CBA these benefits show up as avoided losses.

We may conclude that for direct costs there are differences of opinion: Cochrane offers a broad definition by also including induced physical damage. Parker, Green

and Thompson differentiate between direct and primary indirect costs along the distinction between stocks and flows, and then warn for not summing up direct and primary indirect costs. Rose states that direct costs can be measured either by stocks or by flows. We will come back to this in the next section.

2.2. Indirect Effects in an Economy

Whereas [Parker, Green and Thompson \(1987\)](#) defined indirect costs as business interruptions and multiplier effects in the economy, [Cochrane \(1997\)](#), p. 225) defines indirect economic effects more precise as “*a result of dislocations suffered by economic sectors not sustaining direct damage. Activities that are either forward-linked (rely on regional markets for their output) or backward-linked (rely on regional sources of supply) could experience interruptions in their operations*”. He thus refrains from business interruptions.

In our view (see also [van der Veen et al., 2003](#)), combining the concepts of Cochrane and Rose will solve the existing problem of defining direct and indirect costs: Using a flow-based measurement of economic cost enables the analyst to make a clear distinction between direct and indirect damage. If damage is valued according to a stock-based concept, one is forced to identify property damage as direct damage and to identify damage due to business disruptions as indirect damage. This is not unambiguous since it may introduce double-counting in the analysis. Expressing damage as a flow-based concept gives us an unobtrusive proxy; it enables us to better model indirect damage.

Indirect economic effects are due to relations within an economy. If part of the factories of type B is damaged by a disaster the production of sectors A and C is affected, but also the production of final products (consumption, investment, export and consumption of government) may be hit. From Figure 1 it can be seen that *other* factories of type B in non-flooded areas may take over the production of the damaged factory B.

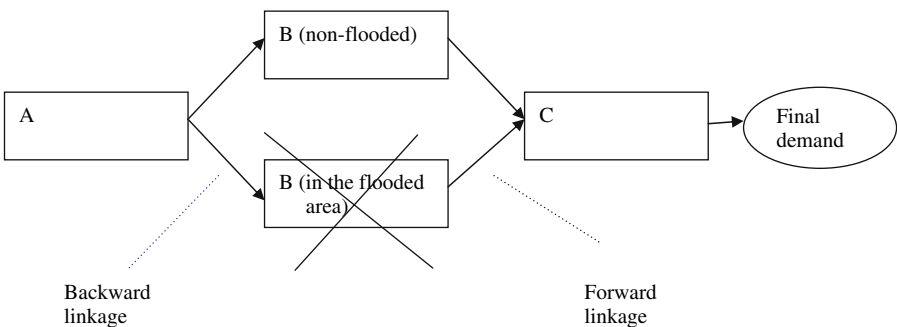


Figure 1. Forward and Backward linkages in an economy, when factory of type B is damaged in a flooded area

The magnitude of these indirect effects depends on: 1) the availability of alternative sources of supply and demand, 2) the duration of the disruption and 3) the possibility to extend production. In general it is very difficult to assess whether alternative sources are available and whether production elsewhere can be relied upon. Detailed market information should be inserted in the model.

2.3. Damage: Towards a Consistent Set of Definitions for Direct and Indirect Costs

To avoid the ambiguities found in the literature² we make the following decisions for the classification of damage:

Firstly, for firms we follow a flow concept to estimate business interruption. For households and governments we apply a stock concept. This means that in our view direct costs relate to 1) physical damage to capital assets, including buildings, infrastructure, industrial plants, and inventories of finished, intermediate and raw materials destroyed or damaged by the actual impact of a disaster. Consequently, 1a) property owned by households and government is measured as changes in stocks, and, 1b) business interruption is estimated as a flow for the duration of the flood. In addition there are 2) non-monetary impacts on households. *Secondly*, in order to estimate indirect economic effects we apply the concept of Cochrane of forward and backward linkages. *Finally*, in order to assess total damage an estimate is required for the excess capacity in production in the non-flooded areas and for changes in economic behaviour of firms and households.

In this paper we will focus on the indirect cost concept in damage estimation and apply it to the case study of simulated flood in the Netherlands. Before doing so, we would like to introduce briefly the input-output analysis as a working vehicle for our estimations.

2.4. Input-Output Analysis

We will highlight here the economic model we use. As suggested by the established literature³ Input-Output modelling makes it possible to look at the inside of the complex inter-industry linkages within an economic system. Input-Output analysis can be described as an economic method that focuses on the trade pattern between the constituent parts of the economy. These parts can be defined in very general terms, such as producers, consumers, the labour force, governmental agencies and foreign countries. Classifications may vary depending on the level of aggregation. For example, on the production side one may wish to distinguish various types of

² *Inter alia* the World Bank, the UN, IIASA and Swiss Re. See also for reference ECLAC (1991) and (2003), Benson and Clay (2000 and 2004), Freeman *et al.* (2003).

³ S. Cole *et al.* (1992), M. Shinozuka *et al.* (1998, pp.95–123), B.G. Jones *et al.* (1997, pp.223–248), Y. Okuyama *et al.* (2003).

industries or sectors such as typical agricultural or industrial sectors, several types of services, *et cetera*. The economic structure itself is modelled in terms of an Input-Output or inter-industry transactions table, which represents the sales from one sector to another. The sales can be between industries, but also between firms and households or between workers and firms.

Row-wise one can observe the intermediate sales and final demand requirements. Former are the sales of goods that are used in the production process. Latter are the sales to households, business investments in fixed capital, government investments and exports. Alternatively, column-wise one can trace 'production functions'. This means that vertically a table reflects all expenditures for intermediary purchases (from various sectors) and other expenses, such as labour, taxes and imports.

The pattern of deliveries is interpreted in terms of regularities in the table, which can be analysed using various mathematical techniques. In conventional notation x is referred to as a vector of total sectoral outputs, f – as a vector of final demand, (Ax) – nominal table of intermediary inter-industry sales and purchases, and A is the symmetric matrix of (constant) input coefficients. Total output of each sector is used for intermediary production and final consumption by households (including exports), which can be reflected as follows:

$$(2.4.1) \quad x = Ax + f$$

The conventional relationship between the total output and final demand is established by

$$(2.4.2) \quad x = (I - A)^{-1} f$$

where $(I - A)^{-1}$ is the economy multiplier matrix also known as the Leontief inverse (see [Miller and Blain, 1983](#), pp. 100–147). Knowledge of matrix A enables us to calculate the effects of shifts in demand via the so-called multiplier analysis. The basic problem in analysing the economic consequences of disasters like flooding or earthquakes is that it requires modelling of *disruptions* in the existing trade patterns. Essentially, we shall try to bring additional consistency to existing modelling.

3. CONSEQUENCES OF A SHOCK TO AN ECONOMY: BUSINESS DISRUPTION

The literature on disaster analysis provides us with several approaches for the problem of estimating the economic costs of a devastating event. However, as we just mentioned, there is still no single unified method available to deal with the consequences of a large-scale disaster, nor there exists an agreement on the exact definitions of major loss concepts. Given the large choice of model variations, we shall first outline the crucial features in disaster model building, looking at a post-flooding situation through an economist's eyes.

3.1. Asymmetric Shock

As the water starts to inundate the region, we will see a large number of production sites affected. In the case of a large-scale catastrophe production in the flooded area might be completely lost for at least a year and might hardly recover during the next year (especially in the Netherlands where water might stay in a polder for a relatively long time – due to the specific geographic features of the country). Therefore, we do not need special theoretical assumptions for the evaluation of direct output damage in the affected area: 100% of production will be lost. We also have to take account of the fact that the flooded factories in general may belong to different branches of industry and that they may be of different size and production capacity. Therefore, aggregating the losses of each production facility and bringing it to the industry level results in what is known as the paradigm of asymmetric shock. That is, different industries within the province (and hence the country) suffer a different level of output failure.

There exist various methods for asymmetric shock implementation. A promising option is offered by [Cole et al](#) ([1993](#), p. 3–13), where a device to formalise the interference into the input-output matrices is presented. He introduces the so-called Event Accounting Matrix (EAM) to trace all the changes induced on the transactions matrix A (see section [2.4](#)). This Event Matrix is meant to absorb the reflections of the changed situation in the production sector in time. Yet the theory behind the EAM is evolving.

As a first step, modelling requires imposing an initial impulse on the whole system. [Rose](#) ([1993](#)) suggests that employment loss coefficients can in principle be used to model the change in output assuming that sectoral output is evenly distributed among employees. Therefore, the chain of causality in our case is as follows. Production changes are assumed to induce final demand changes. That is, we relate the loss estimation data to the final demand dimension of the transactions matrix. We model our *initial impulse* as follows:

$$(3.1.1) \quad \Delta f_j = \varepsilon_j \cdot (f_j)_0,$$

where Δf_j is the final demand change for each sector j ; $(f_j)_0$ is the pre-disaster final demand level for sector j ; ε_j is a fraction of sectoral production lost ($0 \leq \varepsilon_j \leq 1$).

3.2. Production ‘Bottlenecks’

A ‘production bottleneck’ in an economy can be broadly defined as a situation in which overall production is jeopardised by one of the sectors, for whichever reason, so that it is unable to supply the necessary inputs to other sectors. Several causal factors are at work here. The structural factor is the existence of so-called ‘key industries’ in an economy. When, as a result of a natural disaster an uneven loss of production throughout the sectors in the region is observed, these sectors become especially crucial. For example, if a small industry is heavily damaged

(being a highly important source of input for other industries), it will trigger over-proportional losses in other industries, for which it acts as a supplier.

Other causes of the emergence of production ‘bottlenecks’ (let’s call them institutional factors) are imports possibility limitations, payment lags, contract rigidity, etc. As the literature suggests (Cochrane [1997], p. 3; Benavides et al [1998]), the existence of such bottlenecks can substantially raise economic loss expectations.

In the input-output tables a ‘bottleneck’ is reflected as sharply reduced transactions between the industries, which depend most on such key sectors.⁴ Unless an economy can resist the initial shock and adjust, ε_j (see formulae [3.1.1.]) for each sector becomes $\max(\varepsilon_j)$, i.e. down to the level of the most suffering industry.

3.3. Lifeline System

A significant source of additional production disruption in the literature concerns so-called ‘lifelines’. These include infrastructure facilities (roads, railroads, air transport), utilities (electricity, gas, water supply, sewage system) and communication services. Many authors have emphasized their prominent role in contributing to losses.⁵ Many economic transactions depend directly on physical lifeline systems – for example, purchases of power and water by businesses and households, the trucking of goods between the industrial areas and to markets, the flow of information within and beyond the region. Even in cases when a disaster has a limited direct impact on a region under effect, the indirect medium-term impacts might be much more devastating across the local economy, including areas outside the affected region.

Important is the observation that (even) a partial disruption of lifelines brings about larger negative effects than can be viewed directly from an input-output table. As indicated by Tierney and Nigg (1993), “data on the business impacts of the 1993 floods indicate that lifeline service interruptions were widespread, were perceived by business owners as very disruptive, and were a much more significant source of business closure than actual physical flooding”.

Based on the approach suggested by Chang (1997, p.82) and Rose et al (1997, p.96) ‘lifeline disruption effect’ functions can be estimated for each branch of industry. Alternatively, Okuyama et al (2003, p.11) offers to model lifeline collapses via the imposition of final demand drop impulse due to the interruption in lifeline services on the post-disaster input-output table with adjusted coefficients.

⁴ There has been no unanimity over the unified definition of a ‘key sector’ in the literature (see for example Hazari [1970], Beyers [1973]). Nevertheless, the main characteristic usually considered in this kind of analysis is backwards and forwards effects. When a sector has relatively high effects in both ways, there are grounds to conclude that it is an expected candidate for a ‘key industry’ nomination.

⁵ See, e.g. in Cold (1992) and Shinozuka et al (1994).

On top of that, one should also consider that lifeline networks make up a complex lifeline system. The CAE Report (1997), p.12) asserts: “But, most importantly, in most cases there is a high level of interdependency between lifeline services. Each lifeline generally needs the others in some way”. However, Rose et al. (1997) note that modelling the cases involving several lifeline element disruptions is not a straightforward task. The reason is the presence of non-linearity of these interdependency effects. The CAE Report makes a step further, exploring lifeline interconnectedness. It distinguishes between the interdependence of lifeline networks in operation (if A fails, B fails), and in response (need to fix A to get to B).

We recognise the importance of lifeline networks failure as a result of a vast flood, their interconnectedness and loss ‘spillover’ effect on the other sectors, thus leading to the vulnerability of the final indirect loss estimates. Yet, particularly in our empirical example, we are not able to evaluate precisely lifeline disruption effects due to the lack of specific input information about its direct losses. We shall keep lifeline degradation study as an important area of our future research. Though, we suggest that for the time being it can be partially accounted for as a short-run bottleneck for the whole region affected by a disaster.

3.4. Substitution Effect

How do producers react on a shock? The key notion here is *substitution*. Each industry has a number of choices for production and/or consumption substitution. First of all, as a result of a major flood a certain amount of production will be lost. However, production substitutes may arrive through imports. This in effect means that domestically produced goods are substituted for the ones produced abroad. Secondly, after the initial shock to the economy the system adjusts and starts to recover. Due to possible excess production capacities in the rest of the country, producers outside the flooded area may overtake part of lost production. Therefore, with substitution an inter-regional shift of production will be observed⁶ and recovery will have a broader spatial dimension (see also Figure 11). This will obviously moderate the total loss figures for the entire country as economic activity revives.

3.5. Other Factors

At the same time as the flood expands, the population become affected: people loose their jobs and become unemployed. This causes on the one hand a decrease in welfare, and on the other hand additional government expenditures for the

⁶ It should be noticed here that production substitutability highly depends on the excess production capacities of the factories in the areas outside the affected region. This issue also needs additional attention before industry substitution coefficients are obtained.

unemployed. This goes beyond the 'human' face of the story. People lose their homes, need to be evacuated from the flooded area and be settled in other places, which also gives rise to government expenditures, not to mention such intangible effects as the social and psychological impacts. Though these stand beyond the scope of this paper.

Eventually, recovery programmes are launched by governments to soften the consequences of a disaster, namely to help the restoration of the distorted area, the reconstruction of vital lifelines, thus favouring the boost of economic activity. We are not directly estimating the volumes of these investments to include them into the model, though indirectly we take this aspect of recovery into account.

Finally, we have to consider the time aspect of the analysis. First, we witness vast disruptions taking place in the flooded area, spreading also to the rest of the country. Then we observe adjustments of the economy to the new conditions. Not all studies take time dimension into account, although it plays an important role in a coherent economic development when disaster recovery plans are drawn. We will to an extent consider time in our model, as far as we take into account a 2-year time span. We will impose an initial shock on the system, suggesting that the adjustment will start with the second year. We will distinguish between three possible scenarios.

4. THE CASE OF KRIMPEN: CALCULATIONS

4.1. The Data

In our case study we simulate a massive flooding in the Province of South Holland of the Netherlands. This area was nearly inundated in 1953. Flooding was prevented by sailing a boat into the dike breakage.

Delft Hydraulics provided us with the relevant hydrological data with which we are able to compute water depth in a GIS environment. Figure 2 shows the Province of South Holland and the flooded area. In order to compute damage and production loss on the disaggregated level of a GIS it is necessary to combine the geographic characteristics of the inundated area with available aggregated statistics on production and value added for the province of South Holland.

At our disposal we have a data set, which is applied in the Dutch HIS-SSM (Vrisou van Eck and Kok 2001) damage model. The dataset is generated with the D&B Marketeer & Prospector. This data set contains information on location, size (number of employees) and sort of economic activity (expressed in a 4 digit SIC-code) of any place in the Netherlands for the year 2002. The spatial element is a six-digit zip code. Combining the data results in a database in which we have georeferenced data on economic activities (sort of activity and size of activity) per zip code. Schematically, this is represented in Figure 3.

Another set of available structured data is a regional transactions matrix that is used to model the relations in an economy. We use a bi-regional transactions

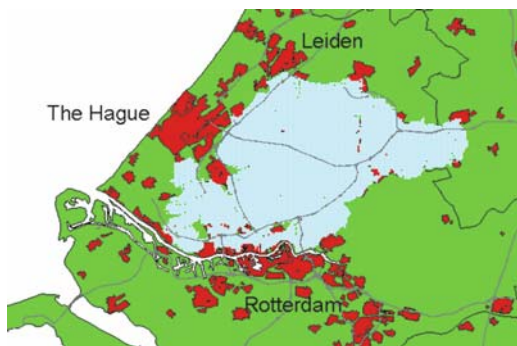


Figure 2. Map of the hydrological model simulation

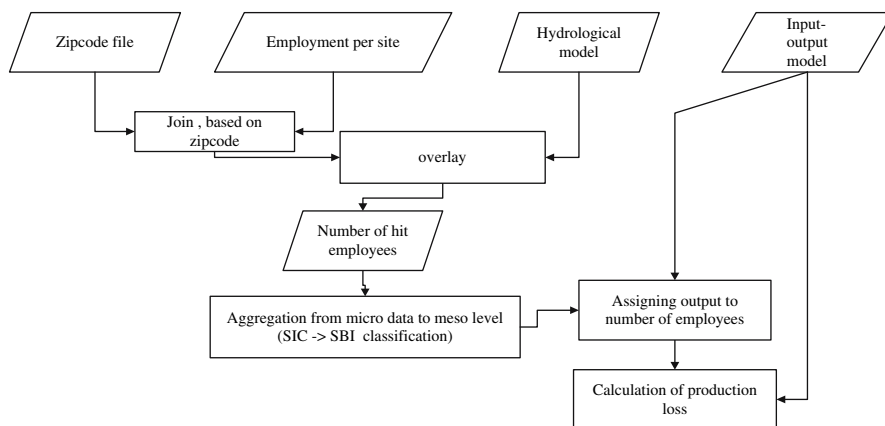


Figure 3. Flowchart of data and data manipulations

matrix in which the economy is represented by the transactions matrix between 39 sectors in South Holland and the rest of the Netherlands. The transactions table was constructed by Groningen University and the Central Bureau of Statistics according to a semi-survey method. The table contains information for the year 1992 on transactions in a SBI format⁷

⁷ With regard to the validity of combinations of the datasets, we should make a reservation. The input-output table itself was set up for the time-period of 1992–1997. This means that the precise data on the transactions may be somewhat outdated. However the literature (Eding, Stelder et al. [1993]) suggests the main characteristics of the economic structure essentially remain unchanged. Therefore, the use of the employment data for the year 2002 for flood simulation under such assumption can be justified. At the same time it is acknowledged that this time-inconsistency of data sets might partially undermine the accuracy of the obtained results.

4.2. Direct Damage Estimation

In Section 2 we concluded that a consistent measure of damage to households is the “stock” measure and that the measure for business activities is the “flow” measure. The damage to households is in our case calculated using the HIS-SSM damage assessment program. Damage to firms (direct and indirect) is assessed by our economic model, based on input-output framework. The latter will be presented in detail in Section 6.

Damage to households refers to the value of replacement of the destroyed objects. In HIS-SSM we take the damage to *infrastructure, buildings and urban property* (for estimates see [Vrisou van Eck and Kok, 2001](#)).

In turn, in order to estimate the direct damage for business activities the vast disaggregated GIS data base with the appropriate GIS software⁸ is coupled with economic and hydrological data to select the zip codes, which are hit by the flood (as also described in [Chang, 1997](#), p.80). This in turn provides us with the number of employees that are affected by the flood.

We obtain the vector of lost employment by sector, ε_j , where each coefficient is calculated by relating the number of employees in a sector that are affected by the flood, by the total number of employees in a sector in the province.

$$(4.2.1) \quad \varepsilon_j^{ZH} = \frac{N_j^{affectedZH}}{N_j^{ZH}}$$

By doing so, we aggregate micro-data to a meso- and a macro- level. The result of this process is a proxy for business disruption that can be used as a starting point to estimate indirect damage.

4.3. Indirect Economic Effects

For our empirical exercise we face a number of problems. One of the major ones: how to introduce business disruption estimates into our transactions matrix (see section 2.4). We do not have information about the intensity of transactions between producers in the flooded area, where activity will terminate, and in the remaining Province of South Holland. This in effect becomes the core issue of the adaptations to be performed during the first stage in our model. There are a number of possibilities in the attempt to overcome this difficulty.

As soon as the direct business interruption damage is assessed and translated into a loss of flow of produced outputs, it is ready to serve as an input for input-output table transformations. There are two possibilities to assess the indirect loss: via the standard model multiplier or with some adaptations of the input-output framework. Exercises along the lines of the latter model are of most interest here; nevertheless

⁸ Arcview (<http://www.esri.com/software/arcview/index.html>).

for comparison we will provide the estimation with the standard model. The standard indirect effects in the course of calculations are obtained with the help of the IRIOS programme.⁹ Adaptations are handled via adjustments for economic resiliency and for the ‘bottlenecks’. We shall thus discriminate between 3 scenarios. For all the cases we look at the loss as a result of 2 years of economic system adaptation to the initial flood shock.

4.3.1. Scenario I –standard exercise

This scenario is presented as a ‘point of departure’ for the comparison with the other two scenarios. It genuinely presents the procedure using the (rigid) standard assumptions of the conventional input-output model.

Step 1. As far as production is interrupted in the flooded area, it causes a decrease of output in the province. The estimate of direct loss due to production activity interruption is provided for each sector in terms of a fraction of lost employment in the province of South Holland (ε_j^{ZH} as in formulae [4.2.1]). It will be multiplied by the vector of final demand to obtain a change of final demand (as a consequence of output drop). Then, indirect production effects will be obtained with a help of simple multiplier.

$$(4.3.1.1) \quad x_0^{St} \rightarrow x_1^{St} : \Delta x_{indirect} = (I - A)^{-1} \Delta f_{direct}$$

As a result, a decrease of the intermediate output level in the South Holland province and in the rest of the country will be observed. Consequently, it will also become reflected in decreased employment throughout the country and in changed imports.

Step 2. Induced effects on the economy are caused by lifeline collapses, which imply extra output losses to the remaining production. An additional decline in activity happens ‘on top’ of the initial shock during the first year after the start of the flood and is introduced in the model via final demand decrease.

$$(4.3.1.2) \quad x_1^{St} \rightarrow x_2^{St} : \Delta x_{induced} = (I - A)^{-1} \Delta f_{lifeline}$$

The calculations for this stage demand additional information about the degree of dependability between the output produced and lifeline services. Unfortunately such information is far more limited and thus the calculations for the additional loss induced by the lifeline system disruption will be omitted for the time being for scenarios I and II.

Step 3. In the second year after the flood production substitution is assumed to take place as a manifestation of economic resilience. This means that lost production of goods in the South Holland during the first year after the flood is overtaken by the same industries found in the rest of the country in the

⁹ The programme has been developed at the University of Groningen, the Netherlands. See also <http://www.reg groningen.nl/irios/irios.html>.

next year. The degree of substitution depends mainly on the existing spare production capacities of factories. The estimation of those capacities requires special surveying, outside the scope of this paper. We will make some simplifying assumptions concerning substitution and consequently a number of alternative outcomes. We will compute the effect of production transfer for all sectors of 10%, 20%, 50% and 100% of the initial shock¹⁰. This means that the respective percentage of lost final demand in the province of South Holland in stage 1 will now be regained in the rest of the country.

$$(4.3.1.3) \quad x_2^{St} \rightarrow x_3^{St} : \Delta x_{substitution} = (I - A)^{-1} \Delta f_{substitution}$$

The standard input-output model exercise assumedly overestimates economic loss (see for example [Rose and Lin 2002](#)). This stems from unchanged multipliers, which actually should be assumed to decrease as production drops implying that a certain fraction of transactions ‘leaks out’ of the economy. Another drawback of this scenario is the rigidity of industry production functions. Alternative assumptions will be discussed in the proceeding two scenarios.

4.3.2. Scenario II – Flexible imports model

In order to keep the results of the different scenarios comparable, the sequence of events is assumed to be the same as described earlier in the standard exercise case. *Step 1.* As a result of a major direct shock production functions in the province of South Holland change. In order to reflect a higher degree of resilience of the system, the over-proportional lost input purchases from the South Holland are now assumed to be compensated by imports. After a correction of the transactions matrix new indirect multiplier effects are obtained.

$$(4.3.2.1) \quad x_0^{FI} \rightarrow x_1^{FI} : \Delta x_{indirect} = (I - A_{Ms})^{-1} \Delta f_{direct}$$

This will have the following consequences: decreased intermediary production level in the South Holland province and in the rest of the country, decreased employment throughout the country and changed imports. The figures can be expected to be of lower magnitude than those in scenario I, step 1.

Step 2. idem scenario I.

Step 3. Following the initial flood shock, the economy responds with production substitution by the respective industries in the rest of the country during the second year. This shift implies a number of adjustments. Because we work with a bi-regional input-output framework, each input coefficient is split vertically into two

¹⁰ These in production substitution assumptions also will help in providing a comprehensive comparison between the modeling scenarios. Imposing the same initial shock and the same degree of production transfer in each scenario, one is able to clearly distinguish between the strength of the resulting effects.

places of origin: South Holland and the rest of the country. Thus, in the after-flood situation under substitution the increased input requirements of all sectors in the other provinces cannot be proportionally obtained from South Holland as the province recovers. Instead, additional inputs will rather come from producers in the rest of the country.

At the same time a positive final demand impulse is given to the economy (characterised by the new substitution-adjusted structure). This may, in principle, be explained as the increased government expenditures including recovery investment. Hence, final loss figures will be more moderate than the effect of the initial shock. The impact is calculated as follows:

$$(4.3.2.2) \quad x_2^{FI} \rightarrow x_3^{FI} : \Delta x_{substitution} = (I - A_{PS})^{-1} \Delta f_{substitution}$$

4.3.3. Scenario III – accounting for ‘Bottlenecks’

Contrary to the previous scenario, this is the one for the ‘black day’ case where the economic system is restricted in response to a vast negative shock.

Step 1. This scenario reflects the result of a production drop as a change in the relationships between economic actors. But in this case the response of the industries in the flood adjacent areas will be much more restricted: we assume here that all the industries in South Holland will be restricted to the level of the sector hit *most heavily* by the disaster. This industry will temporarily act as a ‘bottleneck’ for the rest in the South Holland. This may temporarily happen due to limited access to the area, the time lag needed to establish new contacts to replace lost suppliers and consumers, et cetera. Moreover, the evidence of a sudden large-scale failure of a lifeline can support the emergence of bottlenecks. Therefore, we assume that this scenario approximates the losses incurred by lifeline network disorder. The adjusted input-output table becomes a balanced one through the built up of inventory for the excess supplies and through indebtedness because of increased imports to satisfy final demand. Thus, the trading pattern between the flooded province and the rest of the Netherlands will change, while the production functions will remain constant. We will impose a final demand shock on the new adjusted table:

$$(4.3.3.1) \quad x_0^B \rightarrow x_1^B : \Delta x_{indirect} = (I - A_R)^{-1} \Delta f_{direct}$$

Hereafter, indirect multiplier effects will be obtained. The consequences are expected to be higher than in the previous ‘economy resilience’ scenario.

Step 2. see step 1.

Step 3. During the recovery phase of this scenario, the initially restricted economic system has more room for expansion. Firstly, the maximum loss clause can be relaxed now as after a year the remaining capacity of South Holland can be restored to the ‘natural’ distortion level (with bottlenecks removed). Also, the companies in the rest of the country will tend to increase output, thus creating ‘production transferability’ (this substitution effect will work as described in scenario II). These assumptions call for another adaptation of the economic structure. The re-balancing

of the table will happen through inventory and imports adjustments. The impulses of the increased final demand in the rest of the country will be imposed on the renewed table. These impulses can partially reflect extra government spending on recovery programmes.

$$(4.3.3.2) \quad x_2^B \rightarrow x_3^B: \Delta x_{substitution} = (I - A_{PS})^{-1} \Delta f_{substitution}$$

It's worth noting here that as soon as the economy has more potential to restore it's activity, the recovery will speed up.

4.4. Discussion of Results

Results presented in this section are a fruit of three modelling possibilities. These represent various scenarios for economic response on a large-scale catastrophe. The standard input-output model calculations are given here as a conventional reference point for the other scenarios. Flexible imports scenario suggests an optimistic picture of an economy able to adjust immediately to the sudden distortions. Accounting for 'bottlenecks' scenario models a system, initially paralised by the unexpected shock (indirectly reflecting also lifeline network collapse). In a sense the last model has the highest potential to reflect the possible evolution of disaster aftermath in the most feasible way.

As outlined in the preceding sections, changes in the economy as a result of vast flooding in Central Holland are imposed in an input-output table via an impulse on the final demand and adjustments in the production structure. As a result we are able to trace production level changes throughout the course of calculations. However, note that the main reference category for economic loss evaluation is a change in value added. It acts as a close proxy for a change in GDP, which is also expressed in value-added terms. To refer to the obtained results, consult Appendices 1–3. The tables represent each scenario separately.

To ease the comprehensiveness of the results, Figure 4 is presented here. The graph portrays a vivid picture of possible changes of value added with respect to time for all scenarios, including four substitution alternatives for each of them during the recovery. It is important to note here that although the Graph resembles continuous trends, our analysis is performed for three discreet points in time¹¹

First of all, let us take a look at the order of magnitude for the estimated loss figures. Step one presents the impact brought by the shock. Scenarios I and II suggest, that the initial total loss might overshoot –5%, and the model where the Province of South Holland responds with a highly restricted output to the shock provides with a figure almost twice as that; –9.7% measured in value added terms.

¹¹ Please, also consider with respect to time that the impacts of steps 1 and 2 (from scenario description, section 4.3) are observed by the end of the first year, and impacts of step 3 – at the end of the second year.

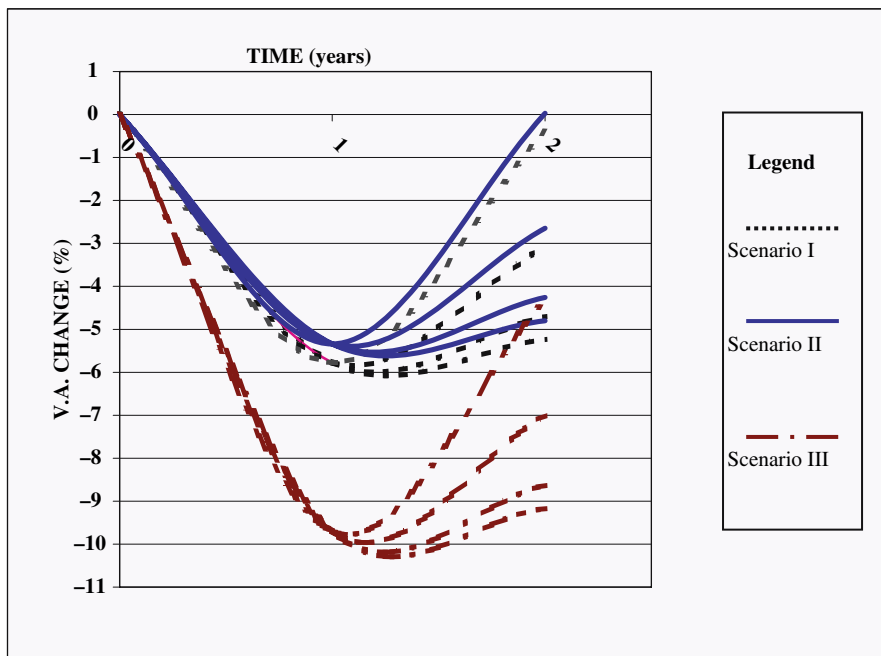


Figure 4. Value added change (%) over time for three scenarios of disaster aftermath

As another general observation one can make is that, the results for scenarios I and II follow each other very closely. Flexible imports scenario is portrays slightly lower loss figures than the ones obtained as a result of standard input-output model use. In turn, the 'bottleneck' scenario presents results that significantly differ from the first two models.

It is of interest to compare the scenarios in observing the effect of various levels of production overtake by the industries in the rest of the country. Whereas a 10% and 20% substitution for all scenarios does not bring much relief, 50% and especially 100% does make a difference. For the standard modelling case, 50% substitution corrects the initial disruption from -5.8% to -3.1% , and a 100% production transfer – up to -0.4% . Similar results are obtained for the adjusted scenario II. For the accounting for 'bottlenecks' model the initial loss estimate is substantially reduced when producers in the provinces outside the flooded region are flexible enough to overtake 100% of the lost output in South Holland. Still, even such extreme behaviour would result in -4.3% loss of value added by the end of the second year compared to the pre-disaster level. Though it seems rather harsh, in the end this scenario might not be that unrealistic. It is the only one that indirectly includes the impact of lifeline disruption.

It may be noted that the differences in the final results stem from the differentials between the scenarios in the first step, where the initial negative flood shock is modelled. Therefore, it can be concluded that the final loss estimate heavily depends on the ability of the economic system to adjust immediately after disaster.

We may draw another conclusion that it is hard for an economy to recover if it operates at full capacity level prior to a disaster. In this case there is no room for production substitution and expansion to take place. Thus, it might trigger the ability of the system to adjust. The same conclusion we may find in Islam (2000, p.159).

The final conclusion to be drawn from the production changes is the economic activity redistribution in the country. As a result of the initial shock and after-phase system adaptations, the relative weight of output in the 'rest of the country' tends to grow compared to the weight of flood-affected South Holland production. This clearly suggests the evolvement of a new structure of the economic system in the entire country.

5. CONCLUSIONS

With regard to methodology development we have made a step forward. We would like to stress the following points:

- 1) The problem of double-counting poses a significant threat of overestimating the overall damage. We expect this possible confusion to be resolved if one explicitly discriminates between stock and flow measurements. Direct damage based on flow estimation gives sound grounds for safe business interruption and indirect damage assessments.
- 2) The standard input-output model is given more flexibility: it has been adapted for modelling the needs of a large-scale flooding disaster. Such crucial elements as 'production bottlenecks', 'substitution effects' and 'time dimension' are included into the analysis of the indirect effects on an economy.
- 3) Pivotal point of the adaptations performed is the assumption about the technology change as a result of a vast devastating flood and its consequences. Thus, we are modelling an economy that tends to adjust continuously.
- 4) Practical problems faced during the empirical estimation for the case of a large-scale flooding in the Province of South Holland involve the joining of data between different data sets (geographically referenced GIS and bi-regional input-output tables, which reflect the structure of economic relations). Providing the employment data with the additional spatial dimension forms the core element of coupling different data sets in our research.
- 5) Empirical economic loss calculations for our case study were performed for the initial shock and the recovery phase. Standard modelling is compared with two alternative input-output table transformation models. As a result it could be shown that a significant difference between the final loss estimates depends substantially on the initial response of the economy to a shock, as well as on the transferability level within the system.
- 6) Further possibilities for methodology extensions and empirical applications should preferably involve software development. More is to be done in the formalisation of the input-output table transformations. Next steps need to be based on additional information concerning induced lifeline disruption and production substitution possibilities. This most likely will bring significant downward corrections to the total economic loss estimates.

APPENDIX 1 MODELLING RESULTS: SCENARIO I [STANDARD EXERCISE]*

		Scenario 1					
			value before the impulse	Direct impulse	Indirect effect	Total effect of impulse	value after the impulse
STEP 1: Initial shock to the economy after the flood		<i>Production (South Holland)</i>	235341	-40679	-9037	-49716	186425
		<i>Production (rest of the country)</i>	790058	0	-8491	-8491	781567
		Total production	1025399	-40679	-17528	-58207	967992
		% production change (w.r.t. pre-disaster output)					-5,60
		% prod. change during the step				-5,68	
		Total value added	593216			-34222	558877
		% value added change (w.r.t. pre-disaster v.a.)					-5,77
		% v.a. change during the step				-5,77	
STEP 3: Recovery (production substitution scenarios)	10%	<i>Production (South Holland)</i>	186425	0	199	199	186624
		<i>Production (rest of the country)</i>	781567	4067	1531	5598	787165
		Total production	967992	4067	1730	5797	973789
		% production change (w.r.t. pre-disaster output)					-5,03
		% prod. change during the step				0,60	
		Total value added	558877			3185	562062
		% value added change (w.r.t. pre-disaster v.a.)					-5,23
		% v.a. change during the step				0,57	
	20%	<i>Production (South Holland)</i>	186425	0	401	401	186826
		<i>Production (rest of the country)</i>	781567	8140	3072	11212	792779
		Total production	967992	8140	3469	11609	979605
		% production change (w.r.t. pre-disaster output)					-4,47
		% prod. change during the step				1,20	
		Total value added	558877			6376	565253
		% value added change (w.r.t. pre-disaster v.a.)					-4,70
		% v.a. change during the step				1,14	
	50%	<i>Production (South Holland)</i>	186425	0	998	998	187423
		<i>Production (rest of the country)</i>	781567	20339	7674	28013	809580
		Total production	967992	20339	8672	29011	997003
		% production change (w.r.t. pre-disaster output)					-2,77
		% prod. change during the step				3,00	
		Total value added	558877			15928	574805
		% value added change (w.r.t. pre-disaster v.a.)					-3,08
		% v.a. change during the step				2,85	
	100%	<i>Production (South Holland)</i>	186425	0	1998	1998	188423
		<i>Production (rest of the country)</i>	781567	40679	15342	56021	837588
		Total production	967992	40679	17340	58019	1026011
		% production change (w.r.t. pre-disaster output)					0,06
		% prod. change during the step				5,99	
		Total value added	558877			31858	590735
		% value added change (w.r.t. pre-disaster v.a.)					-0,40
		% v.a. change during the step				5,70	

* in millions of guilders, basic prices of 1992. [1 Euro = 2.21 Guilders]

APPENDIX 2 MODELLING RESULTS: SCENARIO II [FLEXIBLE IMPORTS MODEL]*

		Scenario 2	value before the impulse	Direct impulse	Indirect effect	Total effect of the impulse	value after the impulse
STEP 1: Initial shock to the economy after the flood		<i>Production (South Holland)</i>	235341	-40679	-16599	-57278	178063
		<i>Production (rest of the country)</i>	790858	0	-8440	-8440	781618
		Total production	1025399	-40679	-25039	-65718	959681
		% production change (w.r.t. pre-disaster output)					-6,41
		% prod. change during the step				-6,41	
		Total value added	593216			-31774	561442
		% value added change (w.r.t. pre-disaster v.a.)					-5,34
		% v.a. change during the step				-5,36	
STEP 3: Recovery (production substitution scenarios)	10%	<i>Production (South Holland)</i>	178063	0	555	555	178618
		<i>Production (rest of the country)</i>	781618	4067	3295	7362	788980
		Total production	959681	4067	3855	7922	967598
		% production change (w.r.t. pre-disaster output)					-5,64
		% prod. change during the step				0,83	
		Total value added	561442			3179	564621
		% value added change (w.r.t. pre-disaster v.a.)					-4,80
		% v.a. change during the step				0,57	
	20%	<i>Production (South Holland)</i>	178063	0	757	757	178820
		<i>Production (rest of the country)</i>	781618	8140	6628	14768	796386
		Total production	959681	8140	7380	15520	975206
		% production change (w.r.t. pre-disaster output)					-4,89
		% prod. change during the step				1,62	
		Total value added	561442			6364	567806
		% value added change (w.r.t. pre-disaster v.a.)					-4,26
		% v.a. change during the step				1,13	
	50%	<i>Production (South Holland)</i>	178063	0	1333	1333	179396
		<i>Production (rest of the country)</i>	781618	20339	16779	37118	818736
		Total production	959681	20339	18119	38458	998132
		% production change (w.r.t. pre-disaster output)					-2,66
		% prod. change during the step				4,01	
		Total value added	561442			15915	577357
		% value added change (w.r.t. pre-disaster v.a.)					-2,65
		% v.a. change during the step				2,83	
	100%	<i>Production (South Holland)</i>	178063	0	2310	2310	180373
		<i>Production (rest of the country)</i>	781618	40679	34295	74974	836592
		Total production	959681	40679	36607	77286	1036965
		% production change (w.r.t. pre-disaster output)					1,13
		% prod. change during the step				8,05	
		Total value added	561442			31852	593294
		% value added change (w.r.t. pre-disaster v.a.)					0,03
		% v.a. change during the step				5,67	

* in millions of guilders, basic prices of 1992. [1 Euro = 2.21 Guilders]

APPENDIX 3 MODELLING RESULTS: SCENARIO III [ACCOUNTING FOR 'BOTTLENECK' MODEL]*

		Scenario 3						
			value before the impulse	Direct impulse	Indirect effect	Total effect of impulse	effect the	value after the impulse
STEP 1: Initial shock to the economy after the flood		<i>Production (South Holland)</i>	235341	-40679	-16530	-59209		176132
		<i>Production (rest of the country)</i>	790058	0	-20796	-20796		769262
		Total production	1025399	-40679	-39326	-80005		945394
		% production change (w.r.t. pre-disaster output)						-7,80
		% prod. change during the step					-7,80	
		Total value added	593216			-57565		535651
		% value added change (w.r.t. pre-disaster v.a.)						-9,70
		% v.a. change during the step					-9,70	
STEP 3: Recovery (production substitution scenarios)	10%	<i>Production (South Holland)</i>	176132	0	503	503		176635
		<i>Production (rest of the country)</i>	769262	4067	3422	7489		776751
		Total production	945394	4067	3925	7992		953386
		% production change (w.r.t. pre-disaster output)						-7,02
		% prod. change during the step					0,85	
		Total value added	535651			3188		538839
		% value added change (w.r.t. pre-disaster v.a.)						-9,17
		% v.a. change during the step					0,60	
	20%	<i>Production (South Holland)</i>	177132	0	759	759		177891
		<i>Production (rest of the country)</i>	768262	8140	6712	14852		783114
		Total production	945394	8140	7471	15611		961005
		% production change (w.r.t. pre-disaster output)						-6,28
		% prod. change during the step					1,65	
		Total value added	535651			6385		542036
		% value added change (w.r.t. pre-disaster v.a.)						-8,63
		% v.a. change during the step					1,19	
	50%	<i>Production (South Holland)</i>	177132	0	1363	1363		178495
		<i>Production (rest of the country)</i>	768262	20339	16914	37253		805515
		Total production	945394	20339	18277	38616		984010
		% production change (w.r.t. pre-disaster output)						-4,04
		% prod. change during the step					4,08	
		Total value added	535651			15965		551616
		% value added change (w.r.t. pre-disaster v.a.)						-7,01
		% v.a. change during the step					2,98	
	100%	<i>Production (South Holland)</i>	177132	0	2499	2499		179631
		<i>Production (rest of the country)</i>	768262	40679	34372	75051		843313
		Total production	945394	40679	36871	77550		1022944
		% production change (w.r.t. pre-disaster output)						-0,24
		% prod. change during the step					8,20	
		Total value added	535651			31966		567617
		% value added change (w.r.t. pre-disaster v.a.)						-4,32
		% v.a. change during the step					5,97	

* in millions of guilders, basic prices of 1992. [1 Euro = 2.21 Guilders]

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CHAPTER 9

A METHOD TO ESTIMATE LOSS OF LIFE CAUSED BY LARGE-SCALE FLOODS IN THE NETHERLANDS

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Abstract: Large parts of the Netherlands lie below sea-level, and the hazard of large-scale floods leading to extensive damage and loss of life is always present. Existing methods to estimate potential numbers of casualties are based on limited empirical data and do not account for evacuation. In this paper a framework for the estimation of loss of life caused by floods is proposed. The method considers different hazard zones in the flooded area and includes the effect of evacuation during the flood. It is applied in two case studies representing a river and a coastal flood in the Central Holland area. The study shows that the possibilities for evacuation during the flood on the number of fatalities depend on the characteristics of the flood, especially celerity of the flood wave, and the location of densely populated areas in relation to the dike break location. Secondly the study shows that contrary to what is generally believed, river floods in the Netherlands may cause a large number of fatalities

Keywords: flooding, flood damage, fatalities, casualties, model, evacuation, escape, coastal floods, river floods, The Netherlands

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1. INTRODUCTION

Every year, floods cause enormous damage all over the world. In the last decade of the 20th century, floods accounted for about 12% of all deaths from natural disasters, claiming about 93,000 fatalities (OFDA/CRED International Disaster Database, www.cred.be). Floods may also lead to other health effects, and can have various physical as well as psychological impacts (Ohl, 2000; WHO, 2002; Hajal, 2003). These health effects may result in indirect delayed loss of life due to stress and illnesses. Increased levels of mortality in the year after a flood are for example reported by Bennet (1970).

Little research has been carried out on the estimation of potential numbers of fatalities caused by floods. An overview of the available methods is given by Jonkman et al (2002) and led to the conclusion that the existing approaches are of limited use for the situation in the Netherlands, as they are based on limited data and do not account for evacuation. The present paper describes the advances in the research on this topic made in the project 'Consequences of floods', which aimed at developing methods to estimate damage to, amongst others, the economy, the infrastructure, and the environment, caused by floods in The Netherlands. The aim of this part of the project was to develop a method to estimate the number of fatalities during river and coastal floods in the Netherlands, taking into account the characteristics of the flood and the effect of an evacuation during the flood.

2. DEVELOPMENT OF A LOSS OF LIFE MODEL IN GIS

2.1. Introduction

Any model that enables estimation of the potential number of fatalities caused by floods needs to consider two elements. First, it must provide an accurate estimate of the number of people present in the flooded area, based on the number of inhabitants and possibilities for evacuation before and during the flood. Second, the model needs to compute the percentage of these inhabitants that will not survive. This percentage depends on flood characteristics such as water depth and flow velocity and on local (area) characteristics, such as the state of buildings and the vicinity of high ground.

2.2. Evacuation

When the estimated number of casualties is based on the total number of inhabitants, the result is likely to be an overestimation. In reality, the number of people affected by the flood will be lower due to the possibility of evacuation before and during the flood. To estimate the number of people that are able to evacuate before the flood water reaches their houses, information is needed about the required time for an evacuation or unorganised escape.

The required time for evacuation can be computed using detailed transport models that account for delays and risk for traffic jams due to, for instance, the presence of cross roads and traffic lights. However, these types of model are often not available as they require an extensive amount of input data. [Barendregt et al \(2002\)](#) developed a more simple conceptual method to simulate evacuation of a flood prone area in the Netherlands. This model mainly considers preventive evacuation before the beginning of the flood. A preventive evacuation consists of three stages: the decision making, initiation of the evacuation, and the evacuation itself. The time needed for each phase depends on, amongst others, the availability of evacuation plans (level of preparedness of inhabitants and local authorities), the number of people to be evacuated and the available infrastructure. An example of an evacuation function is shown in Figure 1.

The available time for evacuation depends on the predictability of the water levels at sea or in the river and the failure mechanism. While extreme river discharges in the Netherlands can be predicted up to several days ahead, extreme sea water levels have a much shorter prediction time (6–10 hours). Failure of a dike is relatively easy to predict in the case of overtopping, but is much more difficult to foresee in the case of the failure mechanism piping/seepage. In the case of evacuation after failure of the dike, the available time only depends on the travel time of the flood wave to a certain location within the flooded area. The time needed for decision making and initialisation in that case equals the time needed to warn people and for the people to prepare themselves for departure. The time required for evacuation depends on the capacity of the infrastructure. In the case of evacuation after failure of the river dike this will mainly be the capacity of the roads, as the railway system is expected to be dysfunctional. Depending on the available time and the required

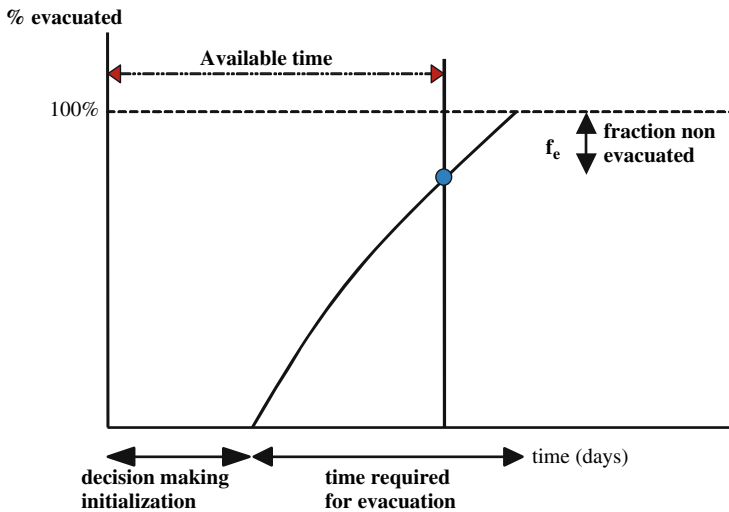


Figure 1. Evacuation curve after [Barendregt et al \(2002\)](#)

time, a certain percentage of the inhabitants will be able to escape in time. The percentage that is not able to escape is indicated by f_e in Figure 11. These persons run a risk of drowning.

As no traffic or transport model was available for the present study, the conceptual function developed by Barendregt et al. (2002) for non-organised evacuation in a theoretical polder area was applied. Based on the study of Barendregt et al. (2002), the total time needed for non-organised evacuation was taken as 50 hours. The time needed for warning and initiation was assumed to take about 4 hours. Different functions were used to assess the sensitivity of the model results for uncertainties in the requested evacuation time. In total, 3 functions were applied. All functions have a warning and initiation time of 4 hours. The total time needed for evacuation or escape, however, varies from 25 to 100 hours. Since high rise buildings provide shelter places during a flood, it was assumed that inhabitants of high rise buildings are safe and can be considered as 'evacuated' regardless of the available time.

2.3. Relationship Between Flooding Characteristics and Loss of Life

A large number of causes for fatalities during floods can be identified (Jonkman and Kelman, 2004). For instance, people can be swept into the water and buildings can collapse. Indirect causes, such as flood-induced heart attacks, shocks and electrocution during the clean up phase can also contribute to the death toll. Several individual vulnerabilities, e.g. age, gender and behaviour, could affect mortality. Quantitative data to analyse the influence of population vulnerability (e.g. age distribution, poverty) on loss of life is not available.

The present study focuses mainly on direct deaths during the flood, amongst those who are unable to escape from the flooded area. So-called flood mortality functions are developed in which the probability of death is statistically related to the flood characteristics, e.g. water depth and flow velocity. The exact cause of death for each individual is not accounted for. The flood mortality relationships are based on detailed data published by Waarts (1992) on casualties caused by the large coastal flood that struck the south-western part of the Netherlands in 1953 and killed 1836 persons. From the available data, three main causes of death are distinguished:

- High flow velocities;
 - Rapidly rising water levels;
 - Other causes, such as hypothermia, heart attacks, shock, failed rescue, etc.
- About 61% of the deaths during the 1953 flood were caused by rapidly rising water levels. Only 15% of the deaths were caused by high flow velocities. The remaining 25% resulted from other causes.

2.3.1. General approach

The model was developed for application for large scale coastal and river floods in The Netherlands. The functions are believed to be representative for floods of low lying areas protected by flood defences. These areas, e.g. so-called polders in

the Netherlands, can be characterised by widespread inundation. The model is less suitable for estimation of loss of life in flash flood areas, dam breaks, or areas prone to localised flooding. Three typical hazard zones are distinguished for a breach of a flood defence protecting a low lying area (see figure 2).

- **Breach zone:** Due to the inflow through the breach in a flood defence high **flow velocities** will generally occur behind the breach. This will lead to building collapse and instability of people standing in the flow.
- **Zones with rapidly rising waters:** Due to the rapid rising of the water people will not be able to reach shelter on higher grounds or higher floors of buildings. This is particularly hazardous in combination with larger water depths.
- **Remaining zone:** In this zone the flood conditions are more slow-onset, offering better possibilities to find shelter. Fatalities may occur amongst those that did not find shelter, or due to adverse health conditions associated with extended exposure of those in shelters.

The distinction between hazard zones is made based on the flood characteristics. The breach zone is used when the flow velocity exceeds a predefined value. A location is in the zone with rapidly rising water if the rise rate exceeds a certain threshold value of 0.5 m/hr. Otherwise a location is within the remaining zone.

For the three hazard zones **mortality functions** have been derived to relate mortality fraction to flood characteristics. Empirical data from historical flood cases will be used to analyse whether a statistical relationship exists between the mortality fraction and certain flood characteristics.

2.3.2. Mortality in the breach zone

Reports from historical floods show that, if breaching occurs in populated areas, mortality can be high in the area behind the breach. Especially due to the high flow velocities and forces associated with breach inflow, buildings can collapse and people can lose their stability. Tests on the stability of persons in flows were carried out by [Abt et al](#) (1989). Collapse of buildings has recently been studied for typical houses in the Netherlands by [Roos et al](#) (2003). The model developed by [Roos et al](#) (2003) takes into account the strength of the type of building, the

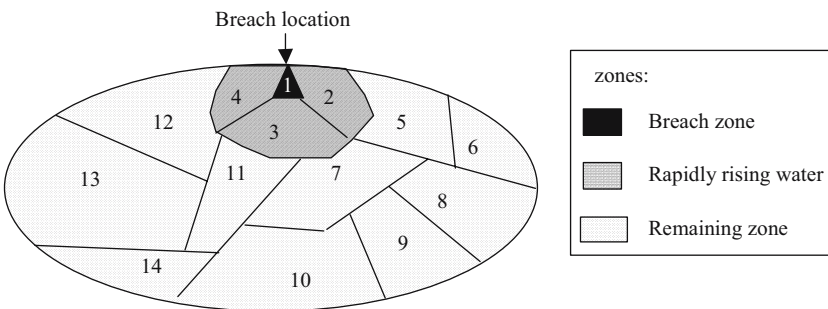


Figure 2. Proposed hazard zones for loss of life estimation for floods due to dike breach

loading caused by water depth, flow velocity and waves, and the relevant collapse mechanisms. A more simple criterion for the damage to buildings under high flow conditions is proposed in the Rescdam project Karvonen et al. (2000). Total damage to masonry, concrete and brick houses is expected to occur if the product of water depth and flow velocity exceeds the following criterion:

$$(1) \quad h \cdot v \geq 7 \text{ m}^2 \text{s}^{-1} \quad \text{and} \quad v \geq 2 \text{ m s}^{-1}$$

with v is the flow velocity (m/s) and h is the water depth (m). This criterion is used in the present study to determine the collapse of buildings and consequently the loss of life of the occupants and accounts for the “immediate impact zone” near the breach. The impact of high flow velocities on human stability is not accounted for separately as the probability of instability will not equate overall risk of being killed in a flood.

2.3.3. Mortality in the zone with rapidly rising water

Rapidly rising water is hazardous as people may be surprised and trapped at lower floors of buildings and have little time to reach higher floors or shelters. The combination of rapid rise of waters with larger water depths is particularly hazardous, as people on higher floors or buildings will also be endangered. The following relationship is derived from the 1953 data (see Figure 3):

$$(2) \quad f(h)_{\text{rise}} = 9.18 \cdot 10^{-4} \cdot e^{1.52 \cdot h} \quad \text{and} \quad f(h)_{\text{rise}} \leq 1$$

$f(h)_{\text{rise}}$ is the fraction of inhabitants killed by rapidly rising water levels (-), and h is the water depth (m). This function should be applied when the water rises at 1 m/hr or more. Extrapolation of this function for larger water depths creates a problem, because no data are available for water depths of more than 3.9 m. As the proposed function is very steep at the upper end, extrapolation may result in

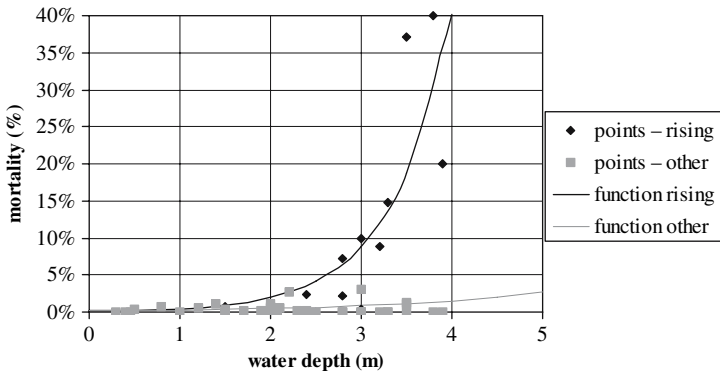


Figure 3. Proposed functions for estimation of flood mortality for rapidly rising water and other causes

unrealistic numbers of deaths. In further research the elapse of this function for larger water depth is to be assessed. Now it is assumed that the 100% value applies to all water depths of 5.3 m or more.

2.3.4. Mortality in the remaining zone

If fatalities are not caused by rapidly rising water levels or high flow velocities, other causes, such as hypothermia, fatigue, heart attacks and electrocution, may result in fatalities. Figure 3 shows the mortalities caused by these causes reported for the 1953 flood. The following function has been derived:

$$(3) \quad f(h)_{\text{other}} = 1.41 \cdot 10^{-3} \cdot e^{0.59 \cdot h} \quad \text{and } f(h)_{\text{other}} \leq 1$$

$f(h)_{\text{other}}$ is the fraction of inhabitants killed by 'other causes' (-) and h is the water depth (m). As these causes of death also occur in slowly increasing water depths, this function is used to estimate the number of casualties in areas with an increase in water depth of less than 1 m/hr.

2.4. Model Framework

To estimate loss of life it is necessary to combine 1) the characteristics of the flood (depth, velocity, rise rate etc.); 2) the number of exposed people (and reductions due to evacuation and shelter; 3) the estimation of mortality amongst those exposed. Figure 4 shows the overall framework of the loss of life model. Ideally, information on the number of inhabitants, the capacity of the available infrastructure and the time of inundation are combined in the evacuation model to estimate the number of people that are unable to escape. This, together with information about the time of inundation, the water depth and the flow velocities is used as input for the so-called flood mortality functions. The outcome consists of a map showing the number of fatalities at different locations within the flooded area. The model is developed with the GIS-package PCRaster (Van Deursen, 1995). GIS data on the number of inhabitants are provided by the Ministry of Public Works and Waterways in the Netherlands (Rijkswaterstaat, DWW). Characteristics of the flood, such as time of inundation, water depths and flow velocities are based on hydraulic computations carried out with a 2 dimensional hydraulic model, developed using the SOBEK model.

3. CASE STUDIES

3.1. Study Area

The lowest part of the Netherlands is divided in so-called dike ring areas, i.e. areas protected against flooding by series of water defences (dikes, dunes, hydraulic structures) and possibly high ground. The study area consists of 'dike ring area number 14', which is located in the western part of the Netherlands and called

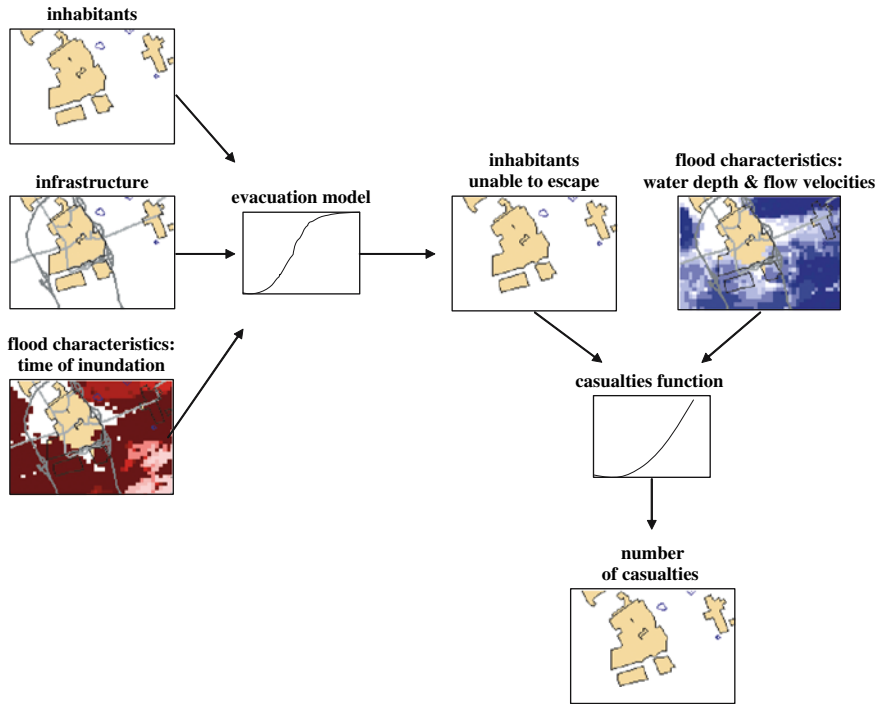


Figure 4. Framework of the GIS-based loss of life model

Central Holland (Figure 5). It is the most densely populated area in the Netherlands and includes major cities such as Amsterdam, The Hague, and Rotterdam. The total number of inhabitants equals 3.6 million. About 10% of the inhabitants live in flats. Dike ring 14 is exposed to different water systems that may cause flooding (e.g. rivers, canals and coasts).

Elevation within the study area varies from about 7 m below mean sea level in the area north east of Rotterdam to more than 25 m above mean sea level in the dune area near the coast (Figure 5b). The main part of the study area is located 1 to 2 m below mean sea level.

3.2. Hydraulic simulations

Hydraulic simulations of the floods in the case study area were carried out with the 2D hydraulic SOBEK model (www.sobek.nl). The most important element of this model is the schematisation of the elevation of the flooded area. Most models that are presently being developed for areas located within The Netherlands use data from the AHN (Actual Height data bank of the Netherlands). This data base consists of detailed elevation measurements (minimum point density of 1 point per 4 m²) carried out using airborne laser altimetry. This data base allows the

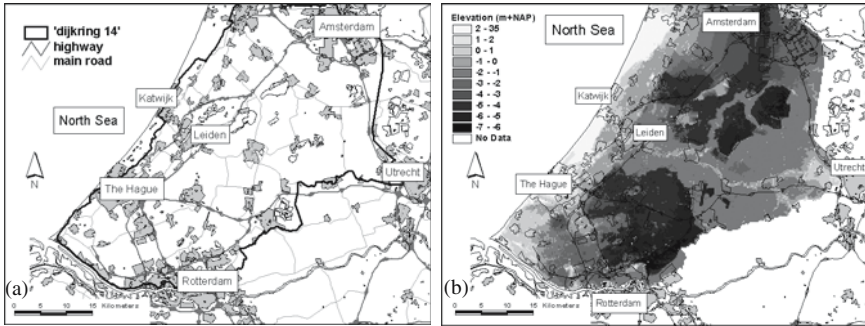


Figure 5. Elevation and topography of the study area 'dike ring 14'

detection of smaller elements, such as railway dikes and highways, whose elevation exceeds that of the surrounding area, and that are important in obstructing the flow. Unfortunately, these recently collected elevation data have not yet become available for Central Holland. Therefore, an older and less detailed elevation model was applied. This elevation model consists of grid cells with a size of $250 \times 250 \text{ m}^2$ and does not include the secondary dike that was constructed in the southern part of the study area. Roads and railway dikes also are absent in this schematisation. This implies that propagation of the flood is seriously overestimated.

Two floods were simulated with the hydraulic model: flooding caused by failure of the coastal defence system near Katwijk, north of The Hague and inundation after failure of the river dike near Krimpen, east of Rotterdam (Figure 5). The hydraulic boundary conditions applied in the model simulations consist of water levels equal to the design water level of 5.75 m above mean sea level near Katwijk and 3.3 m above mean sea level east of Rotterdam (Rijkswaterstaat, 2001) and that are caused by a storm surge in combination with high river discharge. It is assumed that failure near Katwijk consists of failure of an engineering structure (sluice). East of Rotterdam, collapse of the river dike is supposed to be the main cause. The applied gap width is 250 m. The gap is closed after 10 days.

The hydraulic conditions that are applied, the relatively wide gap and the absence of obstacles to the flow, such as railway dikes and the secondary dike east of Rotterdam, result in a worst case scenario. When hydraulic information about the flooded area is needed to develop accurate evacuation plans, the assumptions with respect to the hydraulic boundary conditions and model assumptions need to be reconsidered and a more accurate elevation model should be applied. The model results, however, are suitable for the purpose of this study, i.e. testing and application of the developed loss of life model.

3.3. Results

The main characteristics of the floods as simulated with the SOBEK model are shown in Figure 6. Figures 6a and 6d show the time of inundation computed in

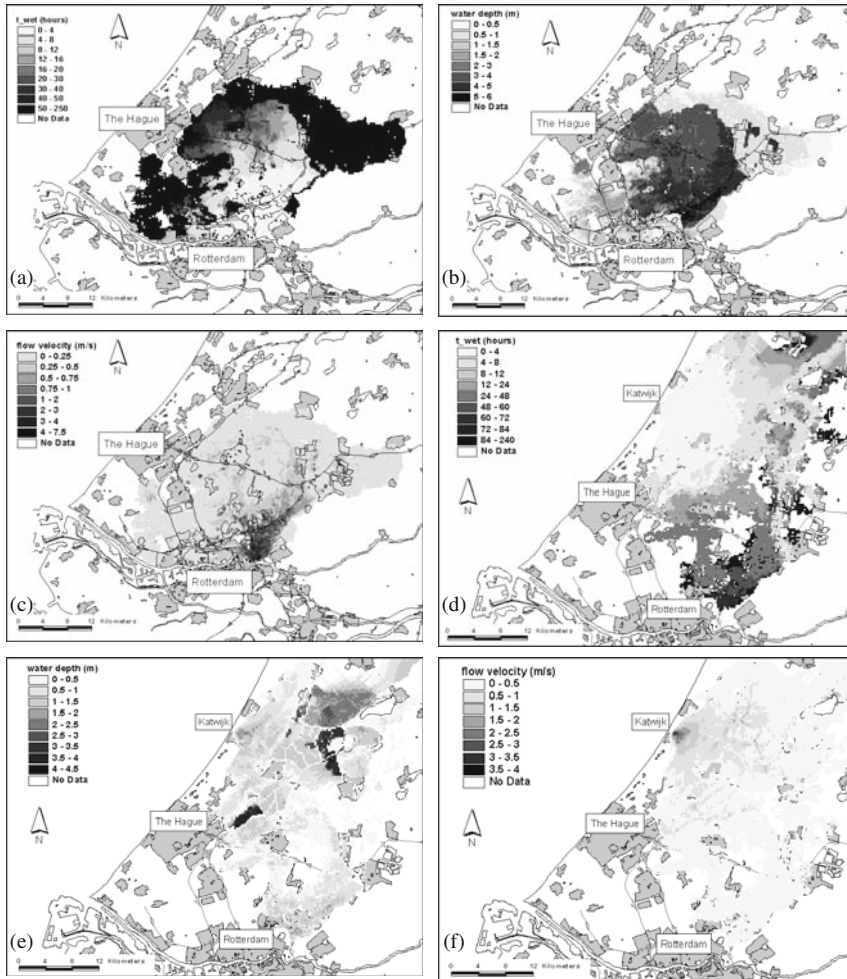


Figure 6. Flood characteristics computed with the 2D hydraulic model: (a) time of inundation Rotterdam case (hours after failure of the river dike), (b) maximum water depth Rotterdam case (m), (c) maximum flow velocity Rotterdam case (m/s), (d) time of inundation Katwijk case (hours after failure of the coastal defence), (e) maximum water depth Katwijk case (m), (f) maximum flow velocity Katwijk case (m/s)

hours after failure of the dike near Rotterdam (6a) and the coastal defence near Katwijk (6d). In both cases, the area near the gap is flooded within a few hours. It takes several days before places near the boundary of the flooded area are inundated. Maximum water depths of about 6 m occur in the Rotterdam case (Figure 6b). In the Katwijk case, water depths generally remain much less (Figure 6e). Maximum flow velocities are found near the gap in the Rotterdam case (i.e. 7 m/s, Figure 6c), whereas flow velocities in the Katwijk case remain lower (i.e. 3 m/s near the inflow location, Figure 6f).

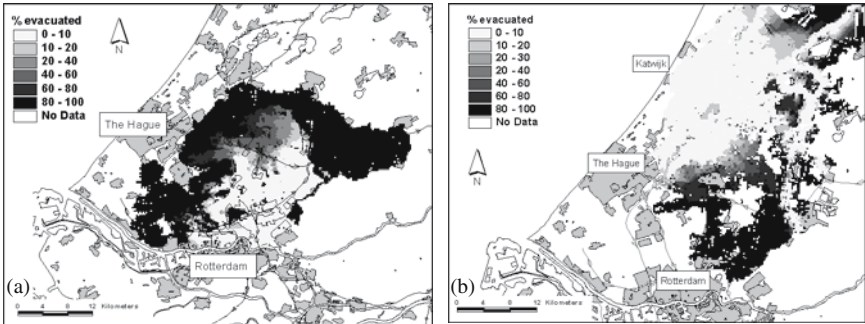


Figure 7. Percentage of inhabitants that can evacuate or escape when the total time required for evacuation equals 50 hours: (a) Rotterdam case, (b) Katwijk case

The percentage of the inhabitants that are able to evacuate before the flood reaches their houses is shown in Figure 7. As is to be expected, the pattern in Figure 7 closely resembles that of the time of inundation (Figures 6a and 6d). Near the gap hardly anybody is able to escape, whereas closer to the boundaries of the inundated area the percentage of inhabitants that is able to evacuate increases to 100%.

The number of fatalities within the flooded area is estimated using the flood mortality functions. It is assumed that people living in high-rise buildings are safe, regardless of the water depth that occurs. The estimated number of fatalities caused by either large water depths or high flow velocities is shown in Figure 8. The results are described in more detail in Table 1 and Table 2.

The criterion for deaths due to high flow velocities only causes deaths near the dike breach in the Rotterdam case. The number of deaths caused by large water depths, in both cases, is much larger. It is likely, however, that the number of fatalities caused by large water depths in areas with rapidly rising water levels

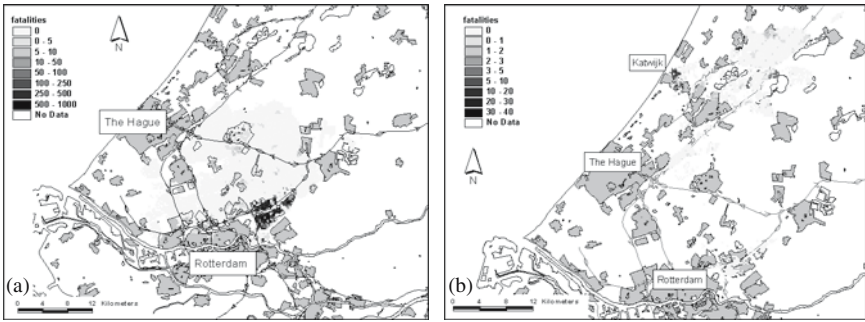


Figure 8. Estimated number of fatalities per grid cell of $250 \times 250 \text{ m}^2$ when the required time for evacuation is 50 hours: (a) Rotterdam case, (b) Katwijk case

Table 1. Estimated number of fatalities using the evacuation function based on a required time of 50 hours

	Katwijk	Rotterdam
nr of inhabitants dike ring area	3.60E+06	3.60E+06
nr of inhabitants inundated area	833720	942334
nr of inhabitants unable to escape	511156	485795
nr of inhabitants unable to escape, living in high-rise buildings	22875	40354
fatalities due to high velocities near breaches	0	5035
fatalities in the zone with rapidly rising waters	181	66453
fatalities in the remaining zone	386	2154
total nr of fatalities	567	71800
% of inhabitants killed	0.06	7.6

Table 2. Estimated number of fatalities using different evacuation functions

		no escape	with evacuation/escape		
			in 25 hours	in 50 hours	in 100 hours
total nr of fatalities Rotterdam	84608		71169 (15.9%)	71800 (15.1%)	72154 (14.7%)
total nr of fatalities Katwijk	731		512 (30.0%)	567 (22.4%)	592 (19.0%)

is overestimated, because of extrapolation of the established relationship between water depth and percentage of people killed (Figure 3). No fatalities occur near the boundaries of the flooded area. This is because almost everybody is able to escape, and because water depths and flow velocities are low.

The results in Table 2 indicate that evacuation during the flood reduces the number of fatalities by about 15% in the Rotterdam case and 20% to 30% in the Katwijk case. The time needed for evacuation or escape has less effect in the Rotterdam case than in the Katwijk case. This is because the area where most lives are lost in the Rotterdam case is inundated within a few hours. Escape during the flood is therefore impossible. Only preventive evacuation may help to reduce the number of fatalities in this area.

3.4. Discussion

3.4.1. Coastal versus river floods

It is often believed that coastal floods are more severe than river floods since the supply of water is unlimited, whereas the inflow through dike breaches along rivers is limited by the discharge through these rivers. However, the case studies showed that in some cases river floods can be much more disastrous than coastal floods (Table 1). Although the total number of inhabitants affected by the flood and the number of inhabitants that cannot be evacuated in time are almost equal, the total

number of deaths varies significantly. This difference is caused by differences in hydraulic conditions. Flow velocities are lower in case of failure of the coastal defence near Katwijk because the water level slope is much less. The difference in river water level and the elevation of the polders near Rotterdam is about 9 m, whereas the difference in sea water level and ground elevation near Katwijk is only about 4 m. Also, the duration of the inflow is shorter in the Katwijk case because water levels at the North Sea decrease after several hours due to the tides and the relatively short duration of the storm. The duration of a flood wave at the Rhine River generally lasts several days or weeks. This results in a smaller total volume of stored water, a slower rise of the water level in the inundated areas and lower water depths in the Katwijk case. The extreme hydraulic conditions in the Rotterdam case result in a very large number of fatalities. River floods at other locations along the rivers Rhine and Meuse in the Netherlands are probably less disastrous as the difference in elevation between river water levels and the elevation of the flooded land is much less. Also, the period during which inflow of water takes place will be shorter at other locations as the water level at the river will drop below the elevation of the flood plain. Near Rotterdam, flood plains are absent so that inflow can continue for a much longer period of time. However, due to the construction of a secondary dike east of Rotterdam, the probability of a flood of this size has become extremely low.

3.4.2. Evacuation

In this study it is assumed that evacuation starts after occurrence of the dike breach and that the flood occurred without warning. This was the case during the 1953 floods. However, due to warning and evacuation before the occurrence of the flood the number of exposed persons and fatalities can be limited. Timely warning should be possible for high discharges on river systems, as these can be predicted in advance. But there is no absolute guarantee that unexpected floods can be prevented as: a) floods from the river can also occur unexpectedly due to sudden dike failure mechanisms; b) prediction and warning times for storm surges (allowing waning times in the order of magnitude of 6–10 hours) will still be insufficient to allow complete evacuation.

In this study evacuation is simulated with a very simple approach. A more detailed evacuation model is needed for a better estimation of the requested evacuation time. A detailed evacuation model is also needed to assess the consequence of the escape route on the risk of drowning. This problem is illustrated with the following example taken from the Rotterdam case.

According to the evacuation model, all people living in Rotterdam-Hilligersberg can be evacuated, since more than 90 hours are available before the flood reaches this area (Figure 2). However, when the surroundings of Hilligersberg are studied, it appears that escape is impossible as Hilligersberg is cut off from the safer areas within a few hours after failure of the dike. In other words: the loss of life model as applied in this case study indicates a very low risk for drowning. However, if the time of inundation of the escape route is taken into account, a very high risk

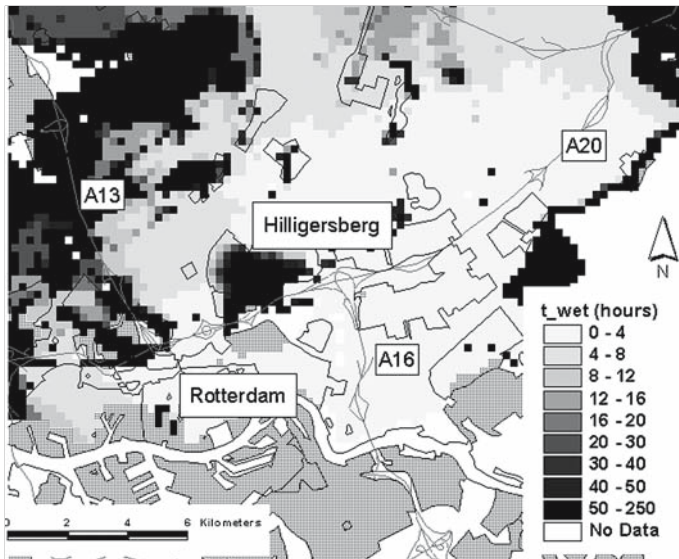


Figure 9. Detailed map of time of inundation near Rotterdam Hilligersberg

appears. The nearest ‘bottleneck’ at the escape route is the road that leads to the highways as well as the highways themselves. The available time to get passed this ‘bottleneck’ to reach a safe area is only 1 hour. It can thus be concluded that when the people living in Hilligersberg try to escape, they run a very high risk for drowning.

A more detailed evacuation model therefore is needed to determine whether inhabitants are really able to escape. Also, insight is needed into the way people react to the risk of flooding. In the case of Hilligersberg it would be better to stay indoor and find a place at the attic instead of trying to escape by car. Good instructions to the people living in areas that have a flood risk may significantly reduce the number of casualties.

3.4.3. Other model improvements

Although one event is used in deriving the relations in the model, the available case is believed to give a representative indication of mortality patterns for the different causes of death. In ongoing research the relations are improved using data from multiple and more recent floods. It is also investigated to what extent the circumstances that affect flood mortality, such as building quality and warning systems, have changed since 1953. This will result in implementation of more detailed relations between flow characteristics, collapse of buildings and fatalities. Special attention should also be given to the number of fatalities that can be expected under very large water depths of more than 4 m.

4. CONCLUSIONS

In this study a new method has been developed to estimate the potential number of fatalities caused by floods. It accounts for evacuation during the flood and is believed to produce more realistic estimates than existing methods that are presently being used in the Netherlands.

The applicability of the model was tested in two case studies in the Central Holland area. Especially the river flood at the location East of Rotterdam resulted in ten thousands of fatalities. However, it should be noted that this event can be considered as a worst case scenario, as (1) no preventive evacuation before the flood was considered, (2) the breach is chosen at a very unfavourable location with low-lying densely populated areas situated near the breach and (3) secondary dikes are assumed absent. Despite these limitations, this case study indicates the catastrophic potential of such a flood. It thus illustrates the importance of sufficient preparation of evacuation and emergency plans.

The case studies indicated that, contrary to what is generally believed, in some instances river floods may cause as many deaths if not more than sea surge events. The main reasons for this unexpected difference are the inflow duration, elevation differential, inundation speed and the location of densely populated areas.

The analysis also showed that the effects of possibilities for evacuation during the flood on the number of fatalities depends on the characteristics of the flood, especially celerity of the flood wave, and the location of densely populated areas in relation to the dike break location.

To improve the fatality model it is recommended to improve the flood mortality functions using data from multiple and more recent floods. The evacuation model can be improved with more detailed transport models and a more accurate consideration of evacuation behaviour.

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CHAPTER 10

AUTOMATION OF FLOOD CONTINGENCY PLANS

Benefits and implementation experiences

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Abstract: In the Netherlands, Water Boards are responsible for the performance of flood defence works. They use contingency plans to handle the complex situation during flood threat situations. Depending on the expected water level, responsibilities change and actions have to be taken. Recent flood threat situations have caused awareness that the human factor constitutes an important risk. Consequently, an automated tool called Geautomatiseerd Draaiboek Hoogwater (GDH/Automated Flood Contingency Plan) was developed

Automation of information management can cause a significant reduction of risk: by using computers for what they are good at (storing information, handling predefined procedures), humans can focus on what they are better at: dealing with unexpected developments and making decisions based on incomparable criteria

During the development of the tool, intense involvement from flood managers is essential. They take part in development of functional specifications, testing of the tool, implementation and finally evaluation, leading to improvement

The result is GDH: a generic tool that any flood risk management organisation can use to automate its own contingency plan and that serves as an information management tool during floods. Main features:

- presentation of all relevant information in a consistent form;
- warnings to the flood manager if required actions are not taken in time;
- automatic communication by fax, text or e-mail;
- automatic logging of all actions (both by system and operator), enabling full post event evaluation;
- basic ingredients of situation reports.

Work is in progress to improve the GDH user interface including full GIS functionality

Implementation of the tool is a major activity. It requires thorough analysis of the existing contingency plans, because GDH demands consistency in the base documentation. As a result, implementation of GDH will often lead to improvement of the contingency plans. After technical implementation, the next step is organisational implementation

Keywords: operational flood management, automation, contingency planning, end user involvement, implementation, information management, geographical information systems, software development, interreg funding

1. INTRODUCTION

In the dike ring system of the Netherlands, Water Boards are responsible for the performance of flood defence works as long as design circumstances are not exceeded. They use contingency plans to handle the complex situation during flood risk situations. Depending on the expected water level, responsibilities change and actions have to be taken. The flood threat situations on the Meuse and Rhine rivers in 1993 and 1995 have caused awareness with the Water Boards that the human factor in operational flood management constitutes an important risk. Consequently, an automated tool called Geautomatiseerd Draaiboek Hoogwater (GDH/Automated Flood Contingency Plan) was developed.

This paper outlines the problem of information management during floods, the properties and functionalities of the GDH tool, the benefits and risks of automation, the development process of the tool (including involvement of prospective users), implementation experiences and further development.

2. INFORMATION MANAGEMENT DURING FLOOD THREAT SITUATIONS

2.1. The Dutch Flood Defence System

Approximately 50% of the Netherlands would be flooded most of the time if it wasn't protected by the elaborate system of flood defence works. The dikes and dunes that provide direct protection from the sea, from the IJsselmeer and from the main rivers are called the primary flood defences; these are more than 3500 km long and include more than 800 structures. Construction, management and safety assessment are formalised in the Law on flood defence. This Law assigns the most important tasks to the flood defence administrators, which in most cases are the Water Boards. One Water Board typically covers 50 to 200 km of flood defence, which means that the dikes of both the Rhine and Meuse are administered by several different Water Boards.

2.2. Dike Rings

The primary flood defences form so-called dike rings, which enclose a total of 53 dike ring areas. The design return period (or the allowed probability of floods) is prescribed by the Law, and varies from 500 years to 10.000 years, depending on the concentration of inhabitants and assets and on the predictability of floods.

For example, the highest return periods are assigned to dike rings Central and North Holland, because of the high concentration of inhabitants and assets and because flooding from the sea has a short prediction horizon. One dike ring can be administered by more than one Water Board, but on the other hand one Water Board can also administer more than one dike ring.

2.3. Tasks in Flood Threat Situations

In flood threat situations, the Water Boards are responsible for the security of the flood defences. The national Department of Public Works (Rijkswaterstaat) is also involved, and is responsible for flood prediction and flood warning. Municipalities and provinces are alerted from an early stage, but only get an active role when public safety is threatened and evacuation is considered. This is a rare occasion (as the high design return periods indicate), but it did occur in 1995. The Water Boards' assessment of the operational security of the flood defences is an important factor in a decision to evacuate.

2.4. Emergency Organisation of the Water Boards

The Water Boards start transforming into an emergency organisation as soon as Rijkswaterstaat measures or predicts a water level above a predefined threshold. This threshold varies for each region, but in most cases has a return period between one and five years. From that moment on, the Water Board follows the procedures that are laid down in a specific Contingency Plan for flood threat situations. The Plan basically consists of typically 3 to 5 water level dependent stages. The decision to enter the next stage triggers a set of predefined actions, and as the water level rises, the organisation structure develops into a full emergency organisation, involving more people and higher level personnel.

2.5. Operational Team and Policy Team

Within the Water Board's organisation, flood threat situations are managed from a central location. From the first stage, an Operational Team is responsible for carrying out the procedures in the Contingency Plan. At later (higher) stages, a specific Policy Team is formed for strategic decisions and communication with other government bodies.

2.6. Tasks of the Operational Team

The Operational Team is the nerve centre of the emergency organisation. All signals from outside, such as the measured and predicted water levels and field status reports arrive at the Operational Team. The Operational Team constantly analyses the situation and considers if specific actions are necessary. It initiates all actions, both predefined and non-predefined, and monitors each action from that moment

on, until the action has been completed. At the earlier stages, most actions are internal (within the organisation), but as the water levels rise, more and more communication with external parties is required. It is essential that the Operational Team is at all times aware of any actions that are delayed or obstructed for some reason, so that it can take measures if required. Finally, the Operational Team has to filter the information that the Policy Team requires for decision making and has to present that information in a concise and structured manner.

2.7. Tools of the Operational Team

Traditionally, the Operational Team has various tools at its disposal for carrying out these tasks. The Contingency Plan itself is a tool: it contains all relevant information that is already available outside the flood season, including the procedures, so it can function as a checklist. Technical data on the flood defences are available from GIS systems. Water level measurements and forecasts are available on-line, both from local stations and from the Department of Public Works. Obviously, communication tools such as e-mail, fax and mobile phones are available, including the national emergency network. At the central Emergency Room, maps of the area play an important practical role. White boards are used as checklists, which is also important for transfer of knowledge between shifts. All activities are registered in logbooks, which serve as input for post event evaluations.

2.8. Need for Improved Information Management Tools

In 1993 and 1995, there were severe flood threat situations both on the Rhine and the Meuse. The discharges were among the highest ever measured and the water levels came within decimetres of the dike crests. The Water Boards carried out their task and followed the procedures in their contingency plans, and in the end 250.000 people were evacuated from a number of dike rings, based on a decision on the provincial level. Post event evaluations showed a profound need for better information management tools, on various levels and for all agencies concerned. Specifically within the Water Boards' organisations, the Operational Team was confronted with information streams of such size and intensity that they were almost unmanageable. As a result, the Water Boards initiated the development of an automated tool for information management during flood threat situations: GDH (Geautomatiseerd Draaiboek Hoogwater/Automated Flood Contingency Plan).

3. PROPERTIES AND FUNCTIONALITIES OF GDH

The development process that was then started has finally led to a generic tool that any flood risk management organisation can use to automate its own contingency plan and that serves as an information management tool during floods and flood threat situations.

3.1. General Use of the Programme

GDH works with a flexible system of password protected user rights, to be attributed by a system manager. All functionalities can be activated through menus. GDH has distinct functionalities for off-line and on-line use; in fact, GDH is at any time either in the off-line mode or in the on-line mode. The off-line mode is normally only used outside the flood season, for updating and maintaining the automated contingency plan. At the start of the flood season, the system is switched to the on-line mode, fixing the automated contingency plan at the same time.

3.2. Off-Line Mode

The off-line mode offers all required functionalities for creating and maintaining the automated contingency plan. The initial translation of the contingency plan into GDH is a major task (see Implementation experiences), but after that the maintenance of GDH is comparable to the yearly maintenance that is carried out on the contingency plan itself. It is customary that the Water Boards check and update their contingency plans each summer season, and that the updated version is formally approved by the Water Board's management team before the next flood season. For GDH, similar procedures can be followed.

3.3. On-Line Mode

The on-line mode is used for the actual operational flood management. Upon starting and logging in, the user enters the default main screen, which shows current water level data and warnings. Through the menu, the user can get several views of contingency plan data, highlighting the current situation. For example, the top half of Figure  shows the stage trigger values of one dike section and the current water level of the two relevant gauges. The current stage is highlighted. The same information can be presented graphically as well, as shown in the bottom half of Figure. 

Water level data from both national and local gauges are constantly and automatically entered (they can also be entered manually). As soon as a water level measurement exceeds one or more of the predefined threshold levels, GDH generates the "stage change advice pop-up". Of course, GDH doesn't automatically scale up or down to the next stage: it is always the responsibility of the flood manager to make that decision.

A decision by the flood manager to change the stage means that all actions that are linked to the new stage become active. GDH presents a list of all these actions, with filters that the user can choose. The list of actions shows all relevant data, including the actual status of each action, which can be updated automatically or by the flood manager. This action window is one of the most important monitoring tools in GDH. Actions will be triggered by GDH using text, e-mail or fax, if this is predefined. Other actions still have to be started by the flood manager himself.

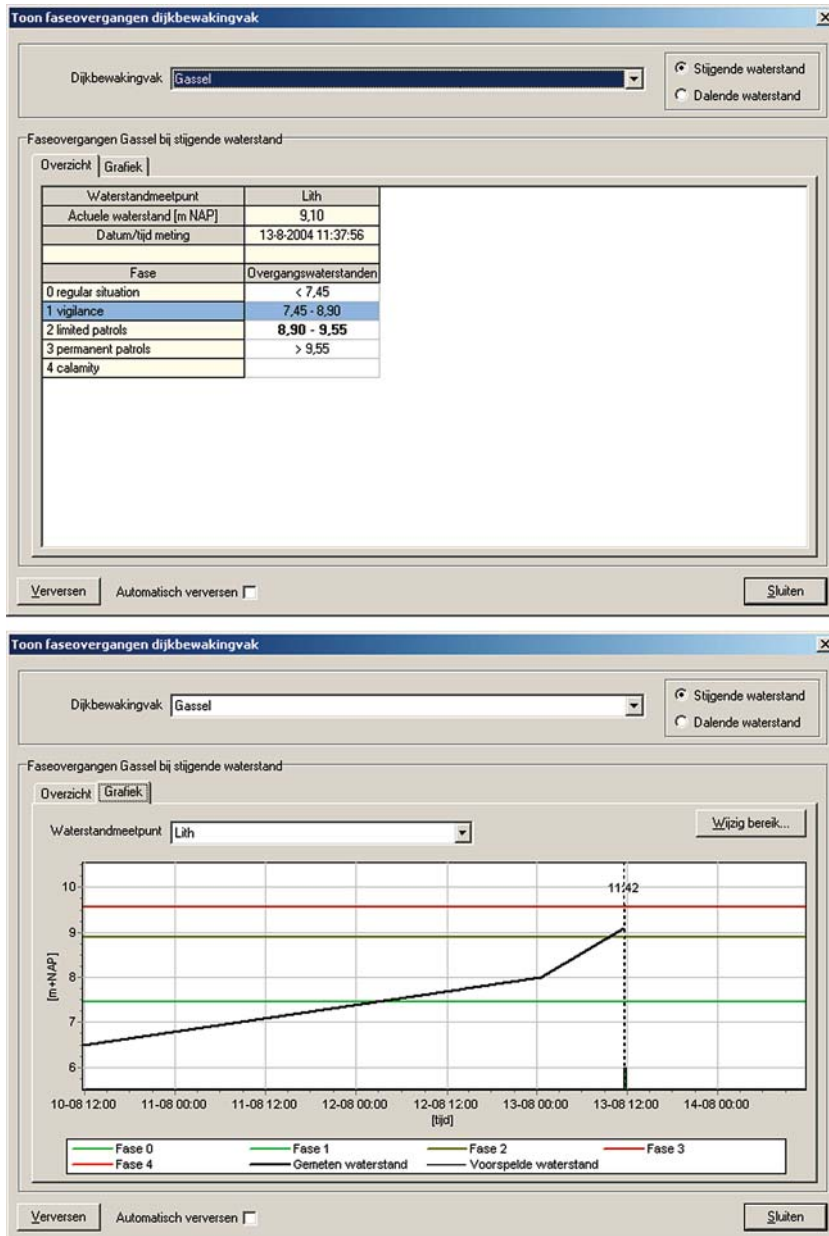


Figure 1. Stage trigger values and current water levels (table and graph)

If response is delayed beyond a predefined limit, GDH will generate warnings (“watch dog functionality”), and if there is still no reaction, a second person can be warned.

Apart from these core functionalities, GDH contains a number of features that can further improve operational flood management:

- The user can find out what actions are required if a certain water level is reached
- During flood threat situations, there are always unpredictable incidents (such as a ship crashing into a lock door), requiring unpredefined actions; GDH can be used for the management and monitoring of these unexpected incidents as well. In such a situation, the incident can be defined, actions can be selected and linked to functionaries, and from that moment GDH treats these actions similarly to the predefined actions
- GDH produces the basic ingredients of a situation report; the user can export these ingredients to include them in his own standard format
- GDH provides GIS visualisation of the emergency situation, providing a clear insight into the current stages and the location of gauges, dike sections, structures and incident sites. An example is presented in Figure 2

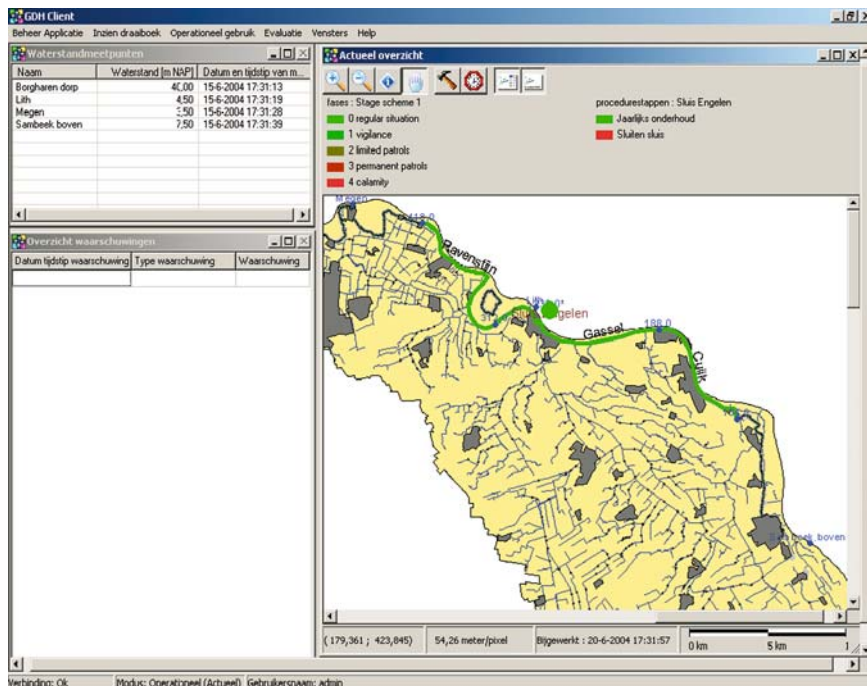


Figure 2. Example of GIS visualisation, on-line mode

3.4. Post Event Use

Post event evaluation is an essential part of emergency management, aimed at improving the contingency plan itself but also at improving the skills of the organisation. GDH keeps a complete log file of all actions both of the users and of the system. The log file can be viewed, saved and printed, using an extensive set of filters. Based on this log file, GDH can produce graphs of water level time series up until any moment within the evaluated flood period, including water level measurements and predictions that were available at that moment.

4. AUTOMATION: BENEFITS AND THREATS

The main **benefits** of automation in this specific case are error reduction, improved understanding, improved efficiency and clear hierarchy and decision structure.

4.1. Error Reduction

Computers are better than humans at storing information and handling predefined procedures. Therefore, automation of these tasks reduces the probability of human errors. In recent years, there has been a development within the Dutch flood control system towards full probabilistic design. The analysis of failure trees has led to awareness that the probability of failure of the dike rings is largely determined by the probability of human errors. Therefore, error reduction has a direct and even quantifiable effect on safety levels! In the specific case of GDH, error reduction is for example caused by the following functionalities:

- Automatic generation of system warnings based on measured and predicted water levels
- Automatic listing of predefined necessary actions depending on the situation
- Better overview:
- Well-organised presentation of necessary actions
- Well-organised presentation of status of actions and responsible persons
- Functionality to sort actions in various ways (show only critical actions or actions for a certain area)
- Automatic control whether actions are executed in time (through generation of reminders)

4.2. Improved Understanding

Computers can sort information and provide presentation facilities, which can improve the understanding of the situation by the user and lead to better decisions. GDH provides:

- Graphical support with area maps
- Continuous availability of situation reports
- Possibility to view the actions that will be required if water levels continue to rise

- Information on the quality of the data (water level data are always accompanied by the date and time of measurement or prediction), leading to better founded decisions
- Utilisation of user profiles in order to limit the information that is shown to specific users of the system
- Standardisation of communication methods within the organisation but also with external agencies or with the public

4.3. Improved Efficiency

Computers can perform standard predefined tasks, and can often perform them better than humans. This can allow humans to focus on what they are better at: dealing with unexpected developments and making decisions based on incomparable criteria. Some GDH functionalities regarding improved efficiency:

- Automatic notification of functionaries using predefined text messages and predefined means (fax, e-mail, text)
- Automatic communication with other Water Board systems (measurement and prediction of water levels)
- Automatic logging of all actions of the system and of users of the system

4.4. Clear Hierarchy and Decision Structure

It is essential that a computer system does not make decisions: it only aids and advises. Moreover, an automated tool can assist in ensuring that all involved persons receive only the information that they require and are authorised to receive. Benefits:

- The systems does not take any decisions; the system only generates warnings and advice for specific users
- Utilisation of user profiles in order to ensure that key decisions can only be taken by specific authorised persons

There are of course **threats** regarding the use of automation in emergency situations. The two main ones are the risk of system breakdowns and the risk that the computer will take over and cause the users to stop thinking for themselves. These threats have played a major part in the development of GDH from the start.

The main threat with regard to *system reliability* is breakdown of communication lines. The vulnerability of GDH to this threat is a function of the level of automation that each organisation chooses. If an organisation chooses to have only one GDH user who communicates with all other functionaries by other means, GDH can be installed stand-alone and communication failure will not affect GDH. One step up is to have more than one user, but to confine GDH use to the central location. In that case, GDH could be vulnerable to breakdown of the central server and the internal network (which are usually well protected). The other extreme is to have GDH users in other offices or even in the field, and they would obviously rely on landlines, mobile communication or internet connections. Reconnection after communication failure is possible, and the user will again have access to the current

situation. Failure of these communication systems would however not affect the functioning of the system within the central location. Finally, there will always be a paper version of the contingency plan, and GDH provides the opportunity to produce this hard copy.

From the start, the Water Boards have stressed that they would never use a system that makes its own decisions. GDH is not more than a *decision support system*: it only carries out predefined tasks when predefined trigger values are reached, and it presents all relevant information in such a way that it supports the user's decision making.

5. DEVELOPMENT PROCESS

The main features of GDH's development process have been intense user involvement and a so-called incremental staged approach: working in several steps and cycles, each with realistic and attainable goals. For the first development cycle that is outlined below the goal was a basic and functioning system, to be available and working before the autumn of 2001. This first cycle consisted of six steps, from the initiative to the final construction and testing of the tool. The same steps can be discerned within each next development cycle.

5.1. Initiative

The Water Boards themselves took the initiative for the development of GDH. In 1998 STOWA, an agency founded by the Water Boards to co-ordinate applied research on water management, carried out a survey among the Water Boards to determine the needs and requirements in the field of flood control. Based on that, STOWA commissioned Royal Haskoning and IKM Engineering to carry out a preliminary study to determine whether a tool such as GDH was worth investing in. Royal Haskoning was responsible for the functional aspects, while IKM Engineering carried out the automation aspects of the study. From the later stages of the process, STOWA hired HKV|Lijn in water to act as process co-ordinator and intermediary between the makers (IKM Engineering/Royal Haskoning) and the actual users, the Water Boards. This division of tasks has been maintained throughout the process.

5.2. Preliminary Study

The preliminary study consisted mainly of a nation wide analysis of the Water Boards' contingency plans and their actual work methods in emergency situations, including interviews with the prospective users of GDH. Based on that, the first sketches of the envisaged tool were drawn, both from a functional and from an automation point of view. A longlist of required functionalities was drawn up, to be prioritised in the following step of the process. Finally, the preliminary study

contained a planning, a cost estimate and a survey into the Water Boards' actual interest in an automated contingency plan. The prospective users were consulted in the interviews, but they were also directly involved in the drafting of the report, as the study was supervised by a steering committee consisting of Water Board representatives. The main conclusions were:

- Though the contingency plans are all based on the same principles and framework, they can differ very much on a detailed level. This means that GDH has to be generic and not rigid in order to be a success
- All surveyed Water Boards are interested in an automated contingency plan; their main interest lies in assistance regarding scenario management, but there are also opportunities regarding communication and presentation

Based on the preliminary study's results, conclusions and recommendations, STOWA decided that it was willing to invest in making a first, basic but fully functioning version of GDH, specifically aimed at the Water Boards situated along the rivers.

5.3. Functional Specifications

The first step in the software development process is the drawing up of functional specifications. The steering committee that supervised the preliminary study was transformed into an active user group, consisting of flood managers of five Water Boards that are situated along the Meuse and the Rhine. The longlist of required functionalities, one of the results of the preliminary study, was analysed and prioritised. A shortlist of functionalities was then selected, partly based on the available time for construction until the next high water season (starting at 1 October of each year).

This shortlist contained the most important functionalities regarding the core of GDH: water level dependent stages that trigger actions, which are in turn connected to persons. This also included 'watch dog functionalities': the user receiving warnings if actions are delayed. Furthermore, automatic input of water level measurements and the possibility to create situation reports were seen as essential functionalities. Finally, a number of requirements were identified that are specifically related to the use of an automated tool: multiple user, stand alone, authorisation and password protection.

The stage that followed was vitally important for the resulting tool. In seven weekly, intensive, four-hour long sessions, all functionalities on the shortlist were specified at a level of detail that would enable construction of the programme in the next stages. Essentially, in this stage the work methods and practical considerations of the flood managers were confronted with the consistency and logic that automation requires. Use cases of all functional aspects were drawn up. A use case is a detailed description of the functions of a part of the system. It describes all the input, all the output, all possible system actions and the underlying logic. Complex user actions and presentation aspects are described in detail by

adding (graphical) examples of screens, tables and graphs. Complex logic is described by drawing up the mathematical relations between input and output.

5.4. Technical Design

A detailed technical design was made before the construction of the programme started. Relevant user aspects in determining the software architecture were the various user types and user locations, the need to update information in various situations and the authorisation structure (for certain actions and for viewing certain information). Examples of technical aspects in determining the software architecture were the necessary connections with other systems (input of water levels, communication by text, fax and e-mail) and the possibility to make back-ups and to log all actions at a central location. The result was a client-server architecture with a detailed description of all internal system actions, the information flows between all components and the data-structure of the programme.

5.5. Construction

The construction of the programme took place in three stages. In the first stage the input and maintenance component for the contingency plans was constructed. In the second stage the component with all functions for use during flood threat situations was added. In the final stage all secondary functions were developed: import, export, connections with other systems, printing, special overviews, etcetera.

The software was constructed using 'Delphi'. Delphi is a 'Pascal' based programming language that allows incorporating complex logic and extensive functions. The software was made by a group of programmers using strict conventions on programming techniques. Main characteristics are object-orientation, special attention to writing clear programming code and special attention to documentation of complex procedures and functions. All programmers' conventions are directed at the possibility to easily understand, maintain and expand the software.

5.6. Testing

Testing is of course an integral part of software development, necessary to verify if the programme works the way it should. Programmers permanently carried out internal tests during the construction of the programme. The user group tested the software after every development stage. There are extra benefits to having an active group of prospective users performing the tests. Testing strengthens the involvement of users, as it gives them a first chance to actually work with the tool that was developed for them according to their requirements. The tests were followed by a series of adjustments to correct errors but also to carry out functional adjustments to incorporate new wishes of users that resulted from new insights during the tests.

The main benefit of testing was that the tests formed the basis for further functional improvement of the tool during the software development process.

5.7. Following Cycles

The development process of the first version of the tool was considered a major success. This resulted in continuing the incremental staged approach during the further development of the tool. Experiences of users were continuously evaluated by the steering committee, which decided to expand the software in several rounds with limited sets of functions. After every stage users tested the software and afterwards started actually using the software. This again resulted in a series of new functional wishes that were evaluated by the steering committee.

6. IMPLEMENTATION EXPERIENCES

GDH is currently being implemented with four Water Boards, who manage the majority of the flood defences along the River Meuse and a significant part of the defences along the Rhine branches. Implementation of the tool within the organisation of the Water Boards is a major activity, involving functional, technical and organisational aspects.

6.1. Functional Implementation

Functional implementation is the actual translation of the existing contingency plan into the automatic format of GDH. Within the context of the GDH project, all involved Water Boards already have a functioning contingency plan that can be used as a basis. The construction of a contingency plan is of course a major project in itself, but that is outside the scope of this article. Functional implementation requires thorough analysis of the existing contingency plans, because GDH demands consistency in the base documentation.

Major decisions at this stage concern the level of detail in which the contingency plan is implemented in GDH. The type of actions in the contingency plan can vary widely, and not all actions may necessarily require the close monitoring that GDH enables. Another aspect is the determination of the monitoring objects: the actual structures and dike sections for which GDH can handle different procedures. Furthermore, a decision has to be made whether the roles in GDH are assigned to staff categories or to actual persons. Finally, the required extent of external communication with other agencies that play a role during emergencies has to be determined.

After that, the actual input of data can take place. First, the basic characteristics of all items are entered. Only in the next separate step, the links between the items are established. The items and their parameters are:

- Monitoring objects (structures and sections of dikes) and their characteristics
- Water level measurement points (gauges) and their characteristics

- Stages
- Actions
- Roles
- Persons and their communication coordinates

The monitoring objects are at the centre of the data structure: all items are in some way linked to a monitoring object, see Figure 3. The most important links are those between:

- Stages to monitoring objects
- Gauges to stages including trigger water levels
- Actions to stages
- Roles to actions
- Persons to roles

The implementation experiences thus far have led to the following conclusions:

- Because GDH requires consistency in the structure of the contingency plan, implementation of GDH will often lead to improvement of the contingency plans. In itself this is an important advantage, but it also means that more time and capacity can be required than expected beforehand
- As discussed, each organisation has to decide on its required level of automation before actually starting the functional implementation. This flexibility is important, because the level of automation determines the cost of implementation, but also the extent of the system. It can be argued that a simple system with a lower level of automation is more transparent, and therefore easier to use and more acceptable to decision makers. Furthermore, there are advantages to starting with a simplified version of GDH and only extend the level of automation

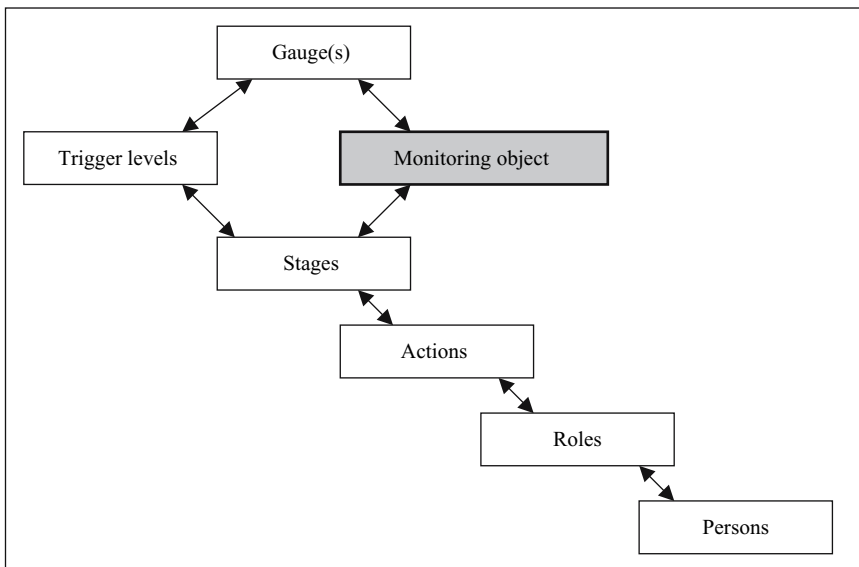


Figure 3. GDH data structure (simplified)

after it has been used and tested in real emergencies, in order to accustom the organisation to GDH.

- Operational teams and Strategy teams often work with different stages, according to their requirements. This requires extra care in the functional implementation.
- The level of detail of the required actions increases as the state of emergency increases. It is appreciated that GDH offers the flexibility to deal with this phenomenon.

6.2. Technical Implementation

Technical implementation involves the purchase and installation of hardware and software. The server has to be installed at the central location, and client stations are required both at the central location and at the field posts. Usually, the required hardware is already available at the central location, but some field posts still have to be equipped with new computers and with the cabling required for communication with the central location.

6.3. Organisational Implementation

The process of implementation doesn't end with the availability of a fully installed and working version of GDH. The objective of risk reduction by automation can only be achieved if all users are familiar with the system, if there is a system of support and maintenance and if the tool is fully validated. Training can be aimed at the respective user types of GDH: the system managers need different skills than the operational users, and there are also different levels within the group of operational users. A support and maintenance system has to be in place, specifically for operational use. Validation of GDH should take place in actual emergency drills (preferably in the framework of regular emergency exercises).

A very important step is the official approval by the Water Board's management that GDH is suitable for operational use, parallel to the current practice that the flood contingency plan is officially approved each September for use in the coming flood season. Initially, the primary tool for flood threat management may still be the paper version of the contingency plan, while the automated version is tested in the background: it will probably take practical experience of its benefits by the flood managers for GDH to be accepted as the primary tool.

7. FURTHER DEVELOPMENT

GDH is already a working tool, but development is still going on. In the first place, this involves improvement of the application within its current scope and user group, but extension of both the scope and the user group is also envisaged.

7.1. Improvement of Current Application

The experiences of the current users during implementation, testing, exercises and operational use will be closely monitored in order to ensure that the correspondence to the flood managers' way of working is maximised. This may involve improvement of the user interface but also extra functionalities.

7.2. Interreg Funding

STOWA has joined forces with flood management agencies from Germany, France, England, Scotland, Ireland and Poland to apply for EU funding with the Interreg IIIB North-West Europe Programme, under project name NOAH. The transfer of knowledge, of expertise and of tools will result in further improvement of GDH and will lead to widening of the scope, for example:

- Improvement of the current GIS functionalities toward a fully GIS based user interface
- Extension of GDH's scope toward an integrated emergency management system with direct links to flood prediction, inundation and evacuation models
- Introduction of palm top interface for use in the field
- Introduction of web interface both for operational users and for the general public, using information filters
- Development of a multi-language version of GDH

7.3. Other Emergency Types

GDH's development until now is based on the specific situation of river flood threat situations in the Dutch organisational structure. However, GDH's programme and database structure are generic to such an extent, that only minor adaptations are necessary to make it suitable for any contingency plan that involves trigger value based emergency stages and requires the monitoring of external actions.

The logical first step within the Netherlands is, to develop specific versions of GDH for flood threat situations in other water systems: coastal flooding and direct inland flooding. The prospective users are the Water Boards' flood managers in this case as well. A preliminary study was carried out, aimed at generating interest and commitment (through interviews and workshops) and at analysing the differences in contingency plans and flood management practices that are relevant for GDH. This study has concluded that there is a significant interest in GDH for other types of flooding, and that the work methods and contingency plans for these emergency types are comparable to such an extent that no specific version of GDH is necessary. There are some additional functional requirements, but they could also be useful for the current users of GDH. STOWA is planning to make an additional application for Interreg funding, aimed specifically at implementing GDH with a wider user group, including realisation of additional requirements.

8. CONCLUSIONS

Recent flood threat experiences and the development toward probabilistic design have demonstrated that the human factor in operational flood management constitutes an important risk.

Automation of information management can cause a significant improvement of safety against flooding: by using computers for what they are good at (storing information, handling predefined procedures), humans can focus on what they are better at: dealing with unexpected developments and making decisions based on incomparable criteria.

Successful development of a computer system for emergency situations requires a maximum of user input throughout the development process.

Throughout Europe, there is a development toward the use of automated tools for operational flood management, not only for prediction and warning, but also for action monitoring, communication, presentation and post event evaluation.

SECTION III

FLOOD ANALYSIS AND MODELLING

CHAPTER 11

THE IMPACT EUROPEAN RESEARCH PROJECT ON FLOOD PROPAGATION IN URBAN AREAS: EXPERIMENTAL AND NUMERICAL MODELLING OF THE INFLUENCE OF BUILDINGS ON THE FLOW

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Abstract: The IMPACT European project addresses the assessment and reduction of risks from extreme flooding caused by natural events as well as by the failure of dams and flood defence structures. The project covers five main research themes, one of these consists in the work package “Flood Propagation”, which particularly focuses on floods in urban areas. The present paper presents some results of the IMPACT project in that field

In a first stage, experiments are conducted in two different scale models. The first series of experiments consists in an idealised dam-break flow against a single building while the second series represents a heavy flood in a simplified urban district with a series of buildings

Parallel to these experiments, numerical strategies are developed for the simulation of floods in urban areas, such as exact representation of each single building, inclusion of the buildings in the topographic data or definition of urban areas as regions with a higher friction coefficient. Those strategies are then tested against the experiments

A variety of numerical strategies were developed by some members of the IMPACT research team. Results of those numerical simulations are then compared to the experiments in order to assess the validity of each proposed strategy. From there, conclusions are drawn with the aim of providing some guidance to future modellers to optimise the flow modelling in urban areas

Keywords: urban floods, flood modelling, flooding experiments, dam break

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1. INTRODUCTION

The IMPACT European project addresses the assessment and reduction of risks from extreme flooding caused either by natural events or by the failure of dams and flood defence structures (Morris, 2002; Morris and Vaskinn, 2002). These structures include, for example, dams, weirs, sluices, flood embankments, dikes, tailing dams, etc. Whilst exceptional, such extreme flood can endanger human life and induce immense economic and environmental damages. This was the case for example during the summer of 2002, when large regions of Eastern and Central Europe were completely flooded. Due to the unexpected high water level in many rivers, several dikes failed by piping, erosion or overtopping. To assess these risks and to prepare effective emergency planning, it is necessary to improve the modelling of resulting flows. This requires a better knowledge of the interaction between flow and structure.

The propagation of catastrophic floods resulting from the failure of a hydraulic structure such as a dike is much more difficult to simulate than natural river floods. Internationally, the most frequently used approach is the USNWS model DAMBRK, but this, in common with other one-dimensional simulations has the following weaknesses: (i) it uses rough approximations for several important processes in a natural river valley, (ii) it provides little information on the interaction of the dam break flow with valley infrastructure and topography, and (iii) it gives no detailed representation of the dynamics of the flow, specifically through urban areas that lie in the path of the flood.

This last point is of particular importance in Europe where urban development leads to a great habitation density. Moreover, dam-break floods in urban areas endanger areas that are normally exempt from natural river flooding and therefore are unprepared for sudden catastrophic inundation. It is thus natural that one of the main research themes of the IMPACT European project consisted in the work package “Flood Propagation”, which particularly focused on floods in urban areas. The present paper presents some results of the IMPACT project in that field.

Concepts and approaches for modelling urban flooding that are investigated in the IMPACT project are of two types: (i) a modification of the flow resistance law to describe the problem at a large scale, or (ii) a detailed representation of the flow processes either by a network of one-dimensional channels or by a thorough two-dimensional approach.

In order to validate numerical models, two experimental works were performed to characterise the flood propagation in urban areas. First, a dam-break flow in an idealised valley with a single building was investigated. Then, experiments on a scale physical model of a city were carried out.

2. SEVERE FLOODS IN URBAN AREAS

The flow resulting from the propagation of a flood wave in urban areas shows some specific features that challenge any modelling. A violent three-dimensional surge forms when the flood wave hits a building, as illustrated in Figure 1 where the



Figure 1. 3D surge against the building in laboratory experiment

picture was taken during a laboratory experiment. The picture in Figure 2 shows a similar surge against a bridge pillar during a real flood in Spain.

Moreover the buildings are generally not aligned with the flow direction. If the building is solid enough to resist, it induces abrupt changes in flow direction. If not, a partial destruction of the building may occur as shown in Figure 3. Such sharp angles and obstacles are common in urban areas as each street crossing results in a new change of direction imposed to the flow.

Moreover, the route of flow in an urban area is ruled by the network of streets linked by squares and crossroads which implies an inter-dependence of tributary flows with different discharges and velocities in each street. Figure 4 shows such an intersection reproduced in the laboratory where cross waves can be identified. Two-dimensional features with re-circulating flows can also occur in such junctions.

Another source of interference for floods in urban areas is the urban drainage system, that either traps water from the streets or rejects water when overflowed.



Figure 2. Flow reflection against the bridge pillar – La Pobla de Lillet, Spain, November 1982



Figure 3. Sharp angle of a house cut by the flood wave in Weisenstein, Germany, during the summer of 2002



Figure 4. Cross waves at an idealised crossroad in the laboratory (UCL)

3. EXPERIMENTAL WORK

Extreme flood events are not frequent and are seldom well documented. Sometimes high-water marks on the buildings allow to measure afterwards the maximum water level, but there is not much more data to gather. In order to be able to predict the consequences of a severe flood by means of a numerical model, this has to be validated and its performances and limits assessed. This is a first reason for performing reproducible experiments that can be well documented. However, what type of experiments should be carried out? There are different levels of interest.

Idealised situations allow to focus only on a limited number of parameters and provide interesting information on specific features. Moreover, it is also necessary to

be able to model numerically simple situations before going to a complex valley with a dense conurbation. A second level consists in scale models of real topographies, but with still simplified parameters. For instance, simple buildings in a complex topography or a complex network of streets but with a simple bed topography. A third level might be a scale model of a real city, which still allows precise and reproducible measurements of the flow data. The final level then consists in the simulation of a real flood event.

This paper presents experiments corresponding to the two first levels, as a key step towards the simulation of real situations. Those experiments were used in a benchmarking session organised in the frame of the IMPACT project that brought together 8 modellers from 6 different institutions, members and non-members of the project.

3.1. The Isolated-Building Experiment

This experiment was designed with the aims of firstly investigating near-field effects and secondly assessing the consequences of the presence of a building on the downstream flow. Near-field effects around the building consist mainly in the formation of hydraulic jumps and of a wake zone behind the building.

3.1.1. Experimental set-up

The experiments were carried out in the laboratory of the Civil Engineering Department of the Université catholique de Louvain (UCL) in Belgium. The channel, sketched in Figure 5, has a total length of 35.80 m and is 3.60 m wide; the cross section being trapezoidal near the bed. The upstream reservoir is 6.75 m long. The dam is represented by a gate located between two solid blocks; to simulate a dam break, the gate is pulled up rapidly. The cross section at the dam location is rectangular and has a width of 1 m. The building consists in a rectangular block with dimensions 0.80×0.40 m and is located 3.44 m downstream from the dam, and makes an angle of 64° with the channel axis. The Manning bed friction coefficient, previously measured under steady quasi-uniform flow conditions, is $n = 0.01 \text{ s m}^{-1/3}$.

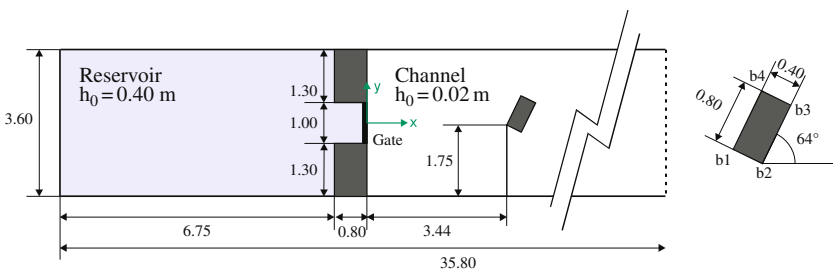


Figure 5. Channel configuration for the single building experiments

The channel is closed by a wall both at the upstream and downstream end. The downstream boundary condition has no influence on the flow during the test duration, which is 30 s. The initial conditions consist in a water level of 0.40 m in the upstream reservoir and a thin layer of 0.02 m of water in the downstream part of the channel.

3.1.2. Measurement devices

The water level is measured by means of 6 water-level gauges located in the channel as indicated in Figure 6: one gauge in the reservoir to monitor its emptying and thus the inflow discharge, and the other around the building. The experiment was run several times and showed a very good reproducibility. The velocity was also measured at the same locations by means of Acoustic Doppler Transducers, but unfortunately, it appeared that those transducers were not adapted to the complexity of the flow (small water depth, presence of numerous hydraulic jumps).

However, a complete surface-velocity field was measured by a digital imaging technique yielding high-quality results. High-speed CCD cameras were placed above the channel to film the flow seeded with tracers at a rate of 200 images per second. This results in a series of images where the white tracers can be clearly identified (Figure 7). Using the Voronoï technique (Capart et al. [2002], Spinewine et al. [2003]) to reconstruct the trajectories of the tracers on the free surface, it is possible to measure the velocity field in the filmed zone.

3.1.3. Flow description

Figure 7 shows a picture taken with the high-speed cameras placed above the channel, where the main flow features can be identified. After the rapid opening of the gate, the strong dam-break wave reflects against the building, almost submerging it, and the flow separates, forming a series of shock waves crossing each other. A wake zone can be identified just downstream of the building, surrounded by cross waves. The flow rapidly reaches an almost steady state with a decreasing discharge due to the emptying of the reservoir. Also, re-circulation zones can be identified between the building and the channel walls.

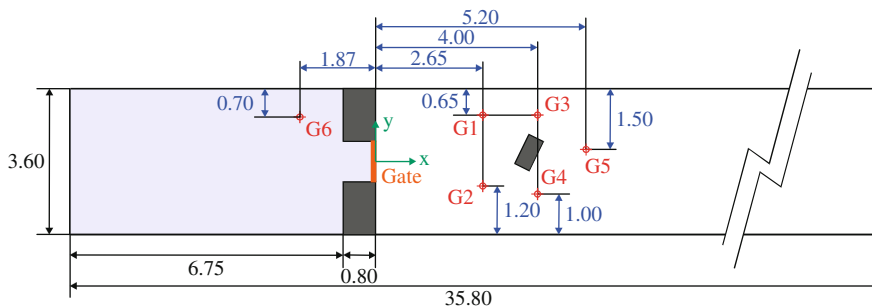


Figure 6. Location of the gauging points in the single building experiment

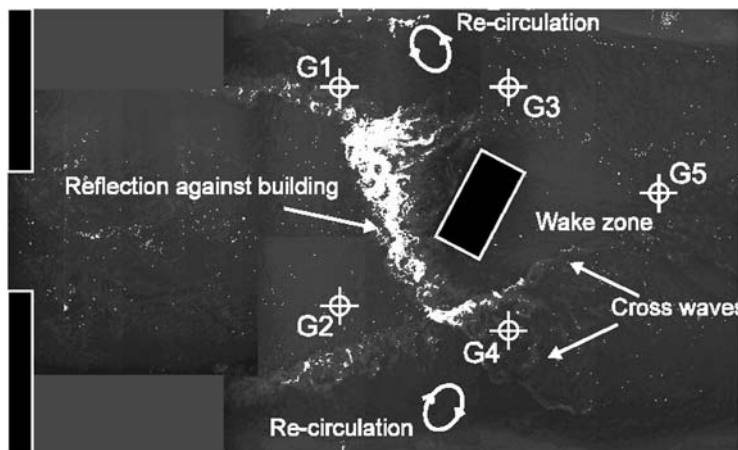


Figure 7. Picture of the flow at time $t = 5\text{ s}$

3.2. The Model City Flooding Experiment

The model city flooding experiment is devoted to studying global flow characteristics of floods in an urban-like environment. Its main purpose is to serve as a benchmark to test the capability of numerical models to accurately represent an urban flood, as will be explained in next section. It is thought of as a complement to the isolated building experiment, in which the detailed characteristics of the flow around a single building withstanding the arrival of a severe dam-break wave are considered.

3.2.1. Experimental set-up

The experiment described here regards the flow arising when a strong flood wave sweeps across the physical model of a city, represented by a certain number of buildings arranged in an ordered pattern as it happens in an actual urban area. It has been performed by CESI (formerly ENEL) at its PIS (Polo Idraulico et Strutturale) facilities in Milano, Italy. The set-up comprises a reduced physical model (scale 1:100) of the Toce river valley that has been extensively used for flood propagation experiments, for instance in the CADAM European concerted action (Soares Frazão et al., 2000). It is a 50 m long concrete model reproducing the topography of the river, fitted with water depth gauges at several locations. A general view of the model can be seen in Figure 8.

In the model city flooding experiment, only the upstream part of the model, about 6 m long, is used. This can be seen in Figure 9 that shows a more detailed view of the area where the model city has been placed. Buildings can be easily identified as concrete blocks forming an ordered pattern. Flooding is achieved by rapidly rising the water level in a feed tank connected to the upstream end of the model by means of a pump. The supply pipe into the feed tank is clearly visible in Figure 9.



Figure 8. General view of the physical model of Toce river



Figure 9. Upstream part of the physical model where the model city has been located (aligned city layout)

upstream of the inflow section. Pump discharge and hence flood characteristics and intensity can be electronically controlled and recorded.

Experiments have been performed with two different layouts of the model city. In one, hereafter called aligned, buildings are placed in rows approximately parallel to the main axis of the valley. This is the configuration shown in Figure 9. In the second, hereafter called staggered, buildings are placed in a checkerboard configuration. Buildings are just concrete cubes of 15 cm side.

Furthermore, in order to separate the effects of the valley morphology on the flow from those caused solely by the presence of the city, some tests have been performed in a simplified model valley: two masonry walls were built parallel to the model longitudinal axis preventing the valley lateral slopes to influence the flow

and also providing a channelling effect. At the same time the bottom of the model between the two walls was flattened out with a concrete layer. This configuration is shown in Figure 10. The total number of buildings that make up the city depends on the urban layout and the valley morphology chosen. The aligned layout on the original model comprises 20 buildings whereas the staggered configuration on the modified valley (the one with two masonry walls) comprises only 14 buildings.

As regards the hydraulic characteristics of the flood, three inflow hydrographs were tested on each valley configuration with a limit on the peak discharge to avoid overtopping of the model buildings. Duration of the simulated flood exceeded one minute in all tests although data recording was stopped at 60 s. The limiting peak discharge depends on the model valley configuration. For the simplified morphology, including masonry walls, tests were run with three hydrographs labelled minimal, medium and maximal, with peak discharges of 60 l/s, 80 l/s and 100 l/s, respectively. The maximal hydrograph drew water elevation to almost overtop the front side row of buildings. The original model valley allows for higher peak discharges without overtopping of the model buildings due to the wider cross section. In this case the three inflow hydrographs used peaked at 90 l/s, 130 l/s and 170 l/s, respectively. Figure 11 shows a typical record of inflow rate versus time that corresponds to a maximal hydrograph on the modified model (with masonry walls) and aligned city layout.

All test were performed with initially dry bed except for the thin film of water left from a previous run in some cases.

3.2.2. Experimental results

The model valley was fitted with 10 water depth gauges, some of them can be seen in Figure 10. The set of depth probes was connected to a computerised data



Figure 10. The simplified morphology version of the valley with staggered city layout

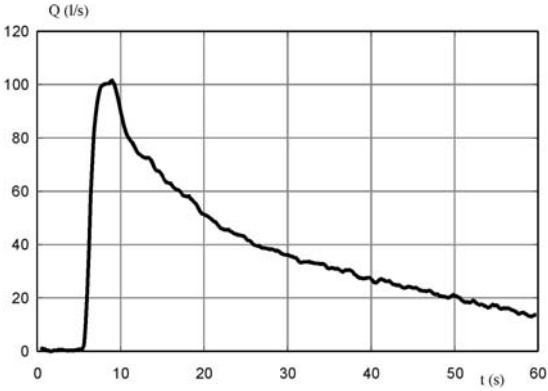


Figure 11. Typical inflow hydrograph curve

acquisition system that recorded water level every 0.2s during every run, thus producing a time series with some 300 data points per probe.

Probes were distributed over the model, focusing on the inlet section, in order to monitor inflow conditions, and around the buildings area. A sketch of the probe distribution can be realised on Figure 12 where probes are marked as numbered crossed circles and buildings as numbered squares. Probe number 1 lies outside the model, in the feeding reservoir and helps monitoring the inflow conditions far upstream. Probe number 2 lies exactly at the inlet section, on the Toce river bed and is the one used to determine the depth at the inflow section. Probes 3 and 4 stand in front of the first row of buildings and probes 5 to 9 inside the model city. In particular probes 4 to 9 surround building number 13 which can be considered at the heart of the town. Probe 10 stands downstream but close to the city.

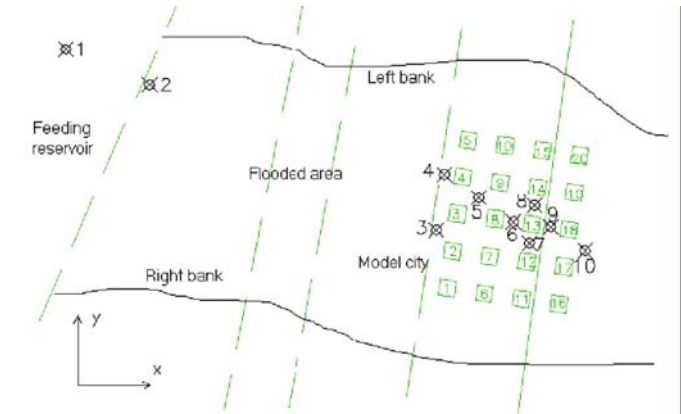


Figure 12. Sketch of the model valley area under study showing probe and building locations



Figure 13. Probe and building locations on the modified valley with staggered city layout

Figure 13 shows the staggered city layout and probe locations on the modified model valley where the two masonry walls are depicted as solid straight lines.

During a test, water is pumped into the upstream feeding tank, its level rises until water flows over the model inlet section and the flood wave propagates in the downstream valley towards the model city. A typical record shows an abrupt increase in water depth when the flood wave reaches every probe that then decreases slowly with time while the model empties. Figure 14 shows the reading of some of the 10 gauges for the test corresponding to the inflow hydrograph displayed in Figure 11 in staggered configuration of Figure 13. The reading of probe number 2 (at the inlet section) is clearly identifiable as the first one to realise the water level

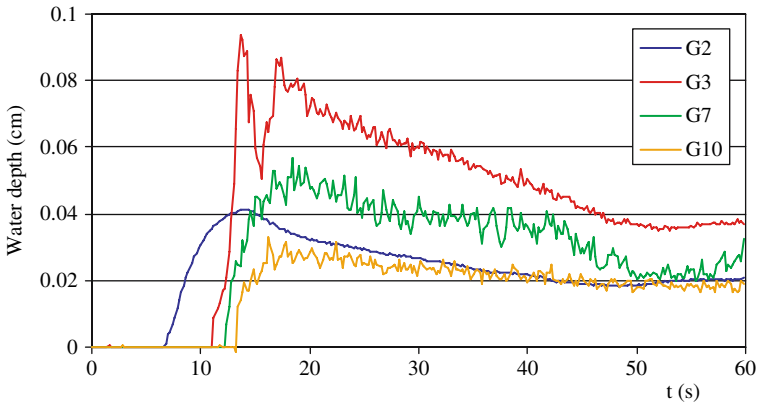


Figure 14. Record of probe readings for the inflow hydrograph of Figure 11 applied to staggered configuration of Figure 13

rise. It exhibits also a clean line as opposed to the downstream probes that display the wave diffraction, reflection and interactions with the buildings.

In order to check for repeatability, every flooding event was run twice. However the pump control system is not capable of exactly reproducing a given inflow hydrograph, and slight differences between data appear in the inflow conditions and hence in the probe readings, but the overall trends and values are very similar.

After analysing the recorded data the general picture of the flow can be described as follows, irrespective of the model valley configuration and city layout: the rapid rise in water level in the feeding reservoir creates a strong flood wave at the inlet section but does not lead to the formation of an abrupt front as would possibly be the case for a dam-break wave. When the first row of houses are hit, a strong, almost stationary front is created while water flows into the city. The front holds for the rest of the event, feeding on the incoming water, and loosing strength as the upstream discharge decreases. The flow inside the city is rich in wave reflections and interactions, that constantly change with time. However considering it as a whole, it looks like if the city acted as a porous medium retaining some amount of water and letting it out slowly. This is in fact the mechanism that holds the standing hydraulic jump in front of the city border. Downstream from the urban area some regions of the flow become supercritical, mainly in the wake of buildings. This can also be viewed as an effect of the strong expansion induced by the increase in cross section after the city area.

Although the general pattern is similar for both valley configurations, some differences are noticeable in the original model valley without masonry walls. Mainly the flow is considerably influenced by the topography and tries to accommodate to the river bed. When approaching the urban area it splits in two branches that surround the city and hence only a fraction of the flood flow crosses it. This leads to lower water levels for the same flood intensity. It must be recalled that this effect is totally absent in the modified valley where the river bed was flattened out and the two masonry walls concentrate the water along the longitudinal axis of the model.

4. MODELLING WORK

This section is devoted to describing the modelling strategies and results obtained during the simulation of flooding events in (model) urban areas. Traditionally this type of flow has been dealt with in a very coarse manner by increasing the roughness coefficient of the regions where buildings are present, with the main aim of reproducing the extension of inundated areas. This is somewhat equivalent to treating an urban region as a porous medium.

The approach adopted here aims at a more detailed description of flood flow within a city in order to be able not only to forecast the inundated area but also the water depth and velocity at any point of interest. This strategy would take into account the wavelike properties of a flood as far as hydraulic fronts can be captured and tracked while they propagate along streets and are reflected by buildings or

other obstacles. A more detailed description of the flow also enables the estimation of risk or danger level based for instance on water depth or momentum flux density at any location.

4.1. Numerical Strategy

The mathematical model adopted is based upon the shallow-water equations (SWE) in two space dimensions that represent mass and momentum conservation on the horizontal plane. This is a drastic simplification of the flow description that in practice involves space and time scales covering more than six orders of magnitude (effects of turbulence, micro and macro topography, etc...) and is clearly three-dimensional. However the shallow water equations represent also a reasonable compromise between complexity and solution affordability. The SWE cast in divergent or conservative form read :

$$(1) \quad \frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = \mathbf{H}$$

with vectors $\mathbf{U}$, $\mathbf{F}$, $\mathbf{G}$ and $\mathbf{H}$:

$$(2) \quad \mathbf{U} = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix} \quad \mathbf{F} = \begin{pmatrix} hu \\ hu^2 + gh^2/2 \\ huv \end{pmatrix} \quad \mathbf{G} = \begin{pmatrix} hv \\ huv \\ hv^2 + gh^2/2 \end{pmatrix}$$

$$\mathbf{H} = \begin{pmatrix} 0 \\ gh(S_{ox} - S_{fx}) \\ gh(S_{oy} - S_{fy}) \end{pmatrix}$$

h , u and v being the water depth and the two Cartesian velocity components in the horizontal plane. Actually u and v represent average velocity components across the water layer of depth h , g is the gravity acceleration, S_{ox} and S_{oy} stand for the bottom slopes in the two co-ordinate directions:

$$(3) \quad S_{ox} = -\frac{\partial z_B}{\partial x} \quad S_{oy} = -\frac{\partial z_B}{\partial y}$$

where $z_B(x, y)$ is the bed elevation which is assumed independent of time in a fixed (non-erodible) bed. Finally S_{fx} and S_{fy} represent the friction slopes (or the slopes of the total head surface) that are usually estimated from empirical friction formulae such as Manning's or Chezy's equation.

The problem to be solved is to obtain the evolution of the water depth $h(x, y, t)$ and the two velocity components, $u(x, y, t)$ and $v(x, y, t)$, for given initial and boundary conditions. Initial conditions frequently consider a dry bed, as would correspond to a normal situation prior to the arrival of the flood. Boundary conditions include inflow and outflow sections as well as material walls such as those representing buildings.

There are now many numerical methods suitable for the solution of the above equations (see for instance the monographs by [Vreugdenhil, 1994](#) and [Tord, 2001](#)). For the particular case of flood flow the method used must fulfil some key properties. Among them it is most important that the numerical scheme be conservative if it is to be able to capture any front in the solution and track its propagation at the correct speed. This property guarantees also mass conservation if properly implemented. Also the discretisation of the convective fluxes and the topographical source terms (i.e. those arising from the bed slope) must be performed in a compatible way in order that spurious, non-physical waves are not generated by the numerical scheme as the work by [Bermúdez et al \(1994\)](#) pointed out.

Most numerical models currently in use for flood propagation perform a separate time and space discretisation. The space operator is most often cast in finite volume formulations and relies upon an approximate Riemann solver ([Tord, 2001](#)) with some enhancements to attain second order spatial accuracy and monotone behaviour. Time integration is explicit in most cases using a second order accurate Runge-Kutta scheme. The reader is referred to the review by [Alicud \(2002\)](#) for a more comprehensive description of the different approaches and corresponding references to the original works.

4.2. Adopted Techniques for Urban Flooding

Flood propagation in an urban region is quite a complex phenomenon due mainly to the topographic complexity of the area. The flow is heavily influenced by the shape and distribution of buildings that, forming streets and squares, divide, divert and merge different streams in which the main incident flow is split. The risks carried by the streams depend heavily on their characteristics that must be accurately forecast if those are to be assessed and, if possible, minimised.

In traditional approaches of urban flood modelling, the city is considered an area of considerably higher roughness than a river bed or a flood plain. Prescription of a proper value for the roughness coefficient of the area in order to reproduce the flood is somewhat arbitrary and some kind of calibration is usually needed. This approach entails a gross description of the flood, usually limited to the extension of the area likely to be inundated, without much insight about the water level attained and the velocity or momentum carried. One could say that this technique just provides a big picture of the flood.

Within the IMPACT project several other possibilities have been explored and subject to benchmarking against the two test experiments described in section three: (i) considering the city as a network of one dimensional channels; (ii) detailed meshing of the town and considering buildings as solid walls; (iii) representing buildings as an abrupt bottom elevation; and (iv) modifying the roughness coefficient.

The first and second strategies are self explanatory and translate into solving the SWE along the streets of the city, either in one dimension (1-D for option i), or in two dimensions (2-D for other options). The 1-D approach is much less

computationally expensive but a two-dimensional treatment seems likely to be more accurate in situations where strong, multidimensional wave interactions are expected.

The bed elevation strategy relies upon solving the 2-D SWE over the city area taking into account the abrupt bottom topography resulting if buildings are considered as part of the bed. In this case, the almost singular source term arising from bed slope is responsible for driving the flood along the streets, unless the flow carries enough head to overtop the buildings.

Finally as regards modification of the roughness coefficient to account for the presence of buildings, a slightly different approach than usual has been adopted. Instead of considering the city area as a region presenting considerably higher resistance, higher friction has been attributed only to the area occupied by every building. The motivation behind this treatment is the hope that the city structure can be better represented by higher resistance zones (occupied by buildings) and lower resistance ones (streets, squares etc...) rather than just by one single value. This is a way of modelling the fine structure of the city at a lower cost than the two previous strategies.

4.3. The Isolated Building Test Case Results

Two types of comparison between experimental and numerical results can be made: the water level evolution at the 6 gauging points and the velocity field over the whole area around the building. The numerical results presented here were obtained by means of a two-dimensional finite-volume scheme using a Roe solver for the fluxes. The scheme is first-order accurate. The computational domain consists of 38880 quadrangular cells. The building and the blocks forming the dam are represented as walls in the mesh.

4.3.1. Water level

The water level evolution at gauges G2 and G3 is presented in Figure 15. Gauge G2 (Figure 15a) is located upstream from the building and records the arrival of

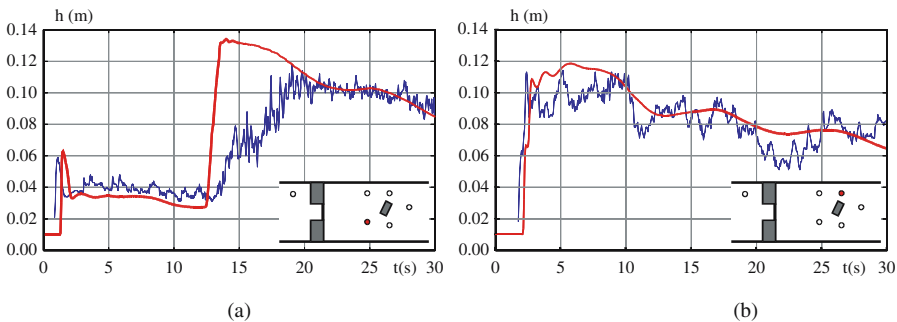


Figure 15. Comparison between experimental (—) and numerical (—) results at (a) gauge G2 and (b) gauge G3

the reflected wave around 13.6 s. The reflected wave is well reproduced by the numerical model, but its arrival time is slightly underestimated, which means that the wave travels faster in the numerical model. The water level is rather well computed, except the amplitude of the reflected front which is overestimated, probably due to three-dimensional effects not taken into account in the 2-D shallow-water approach.

Gauge G3 (Figure 15b) is located on the left side of the building, immediately downstream from it, in a region with re-circulating flow and cross waves. The overall agreement of the computed results with the experiments is good. However, the waves on the free surface are not reproduced with all the details. There are two main reasons for that. First, as already mentioned, there is a re-circulating flow in this region, due to turbulence effects that are neglected in the shallow-water equations. Secondly, as the numerical scheme is only first-order accurate, the numerical diffusion damps out the fine wave structure in the computed results.

4.3.2. Surface velocity

The measured and computed surface-velocity fields at time $t = 5$ s are shown in Figure 16. The corresponding computed water depth is shown in Figure 17. Figure 16a corresponds to the experimental data obtained by the digital imaging technique developed by Capart et al. (2002) and Spinewine et al. (2003). Some regions of the figure appear to be empty. In fact, this corresponds to regions where no tracers could be identified.

The two-dimensional spreading of the dam-break wave can be clearly observed on both Figures 16 and 17 as well as the separating flow around the building. The wake zone behind the building is also well reproduced as a region with a low water level (Figure 17) and a low velocity (Figure 16).

However, some discrepancies can also be observed. The change in direction of the velocity vectors (Figure 16) is much smoother in the computation than in the reality. This is consistent with the observation made in the previous section that the numerical flow is artificially smoothed by the numerical diffusion, which dissipates a part of the energy needed to redirect the flow. Also some features are not represented, for example the 3-D effects due to vertical velocity components. Besides, when looking closer on the region situated on the left side of building, at the left end of the hydraulic jump, a re-circulating flow is present in the measured data, that is not reproduced in the computation.

Generally speaking, the overall agreement between computed and measured velocities is good, but improvements are still possible. It must be outlined that such an analysis is feasible thanks to the refined experimental results obtained by the digital imaging technique.

4.4. The Model City Flooding Experiment Test Case Results

The model city flooding experiment provided a large set of data for the different combinations of valley topography, model city layout and inflow hydrograph.

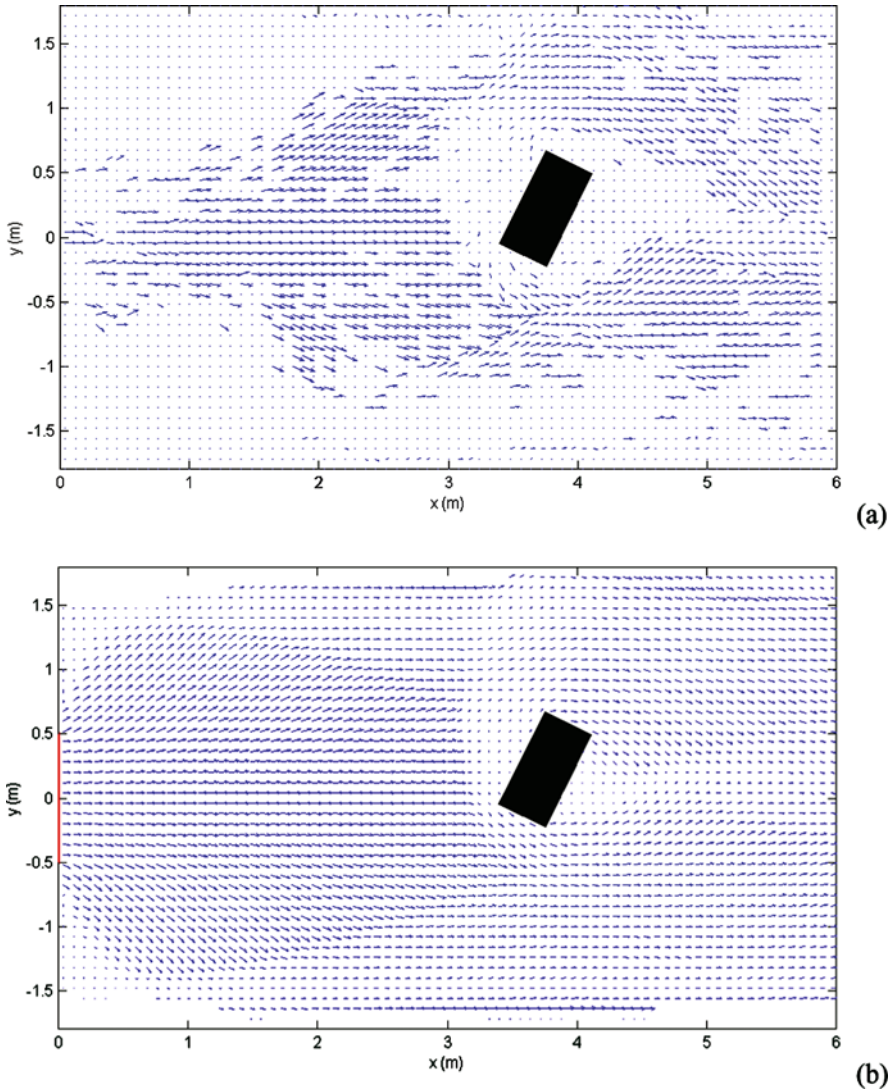


Figure 16. Velocity field at time $t = 5$ s, (a) experimental and (b) computed

Numerical computations have been performed for many (but not all the) configurations with several models. However only a very abridged set of results obtained with a single model will be discussed here due to space limitations. Nevertheless the general performance trends are good representatives of what can be expected from other SWE models.

The particular model uses a finite volume discretisation on multi-block structured grids (quadrangles) based on Roe's Riemann solver and variable extrapolation.

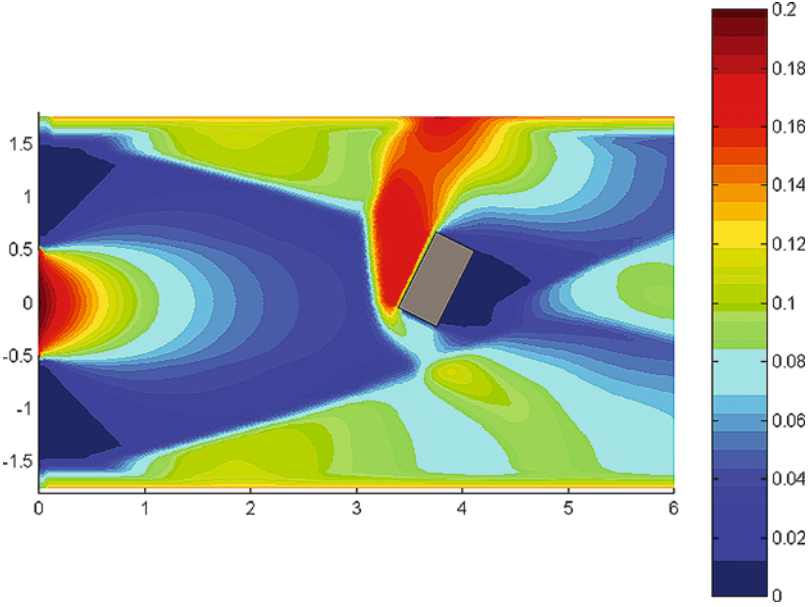


Figure 17. Computed water surface at time $t = 5$ s. All units in m

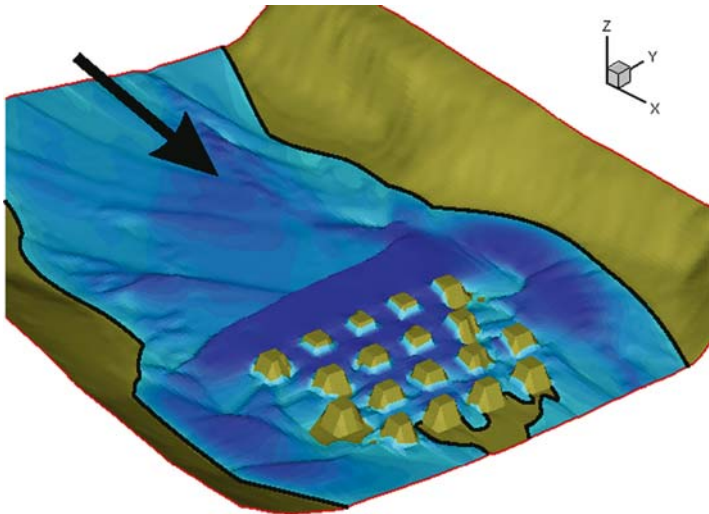


Figure 18. Perspective of a simulated flood on the original model valley at time $t = 14$ s

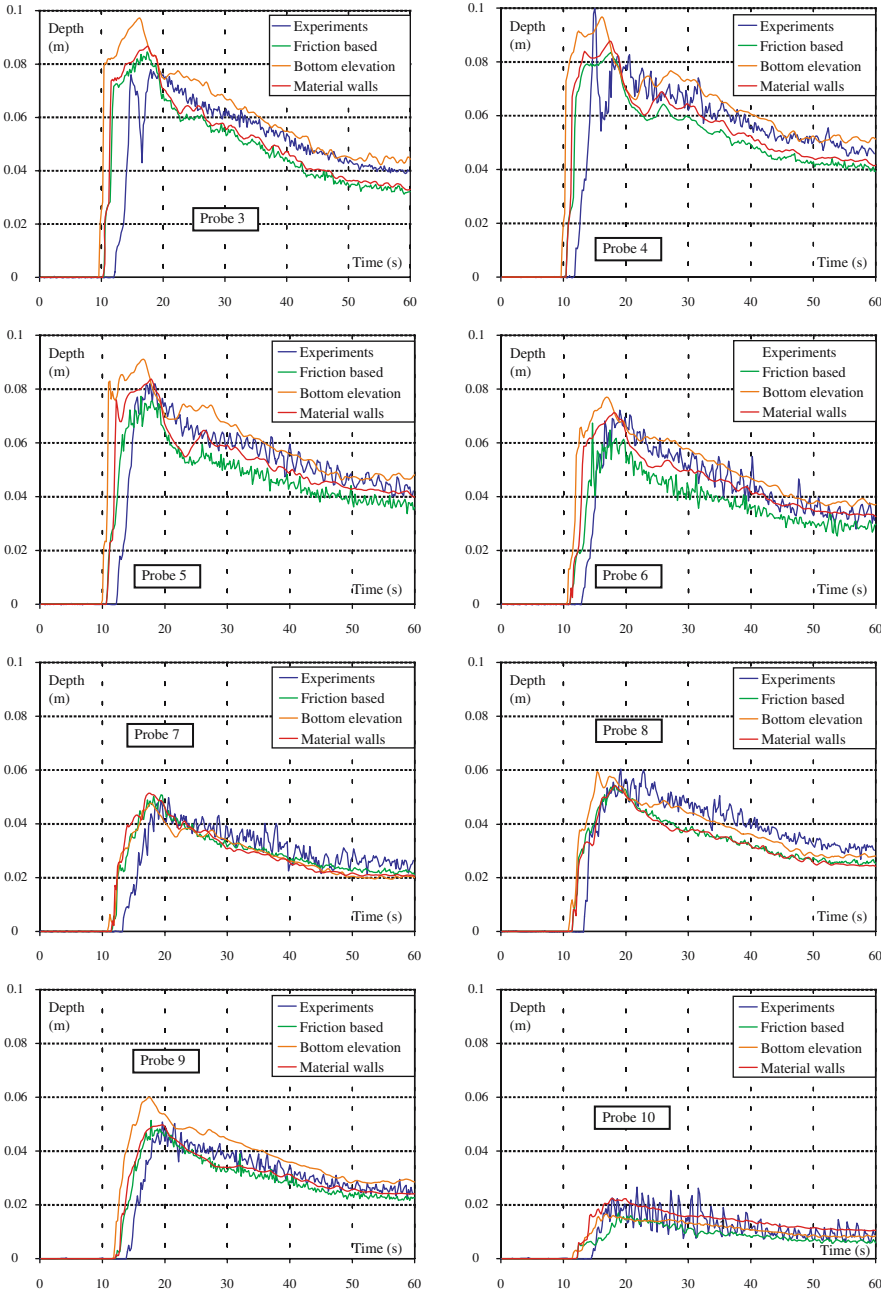


Figure 19. Comparison of simulated and measured water depth at the probes for a typical run

Time integration is two step Runge-Kutta with overall second order accuracy (space and time). The recorded pump discharge was imposed as an inflow hydrograph for the upstream boundary condition. As regards the representation of buildings, the four techniques described in paragraph 4.2 above were used. Free flow was imposed as downstream boundary condition although this is not completely realistic because the physical model continues several tens of meters downstream. A general picture of a simulation result on the original model valley at $t = 14$ s can be seen on Figure 18.

In the set of plots under Figure 19 the computed water depth is compared to the experimental probe records for three different building representations: approach (ii) considering the building as material wall, approach (iii) representing the bottom elevation of the buildings, and approach (iv) that is friction based approach. The scale is kept the same for all of them in order to show the relative water depths at different points. The test case corresponds to the staggered city layout on the channelled model valley with the minimal inflow hydrograph (60 l/s).

As the picture makes clear, Probes 3 and 4, located at the front line of the model city are the first ones to be hit by the flood. This is signalled by an abrupt rise in water depth. Probe number 5, in front of the second row of buildings, suffers approximately the same hit because in the staggered configuration there is no building ahead of it. The next four gauges (numbers 6, 7, 8 and 9) surround block number 13, in the third row of buildings, and the flood wave has been already considerably attenuated. Finally probe 10 is located in the wake of block 17, in the last row of buildings, and the water depth attained there is considerably lower.

It is clear from the graphs that all three approaches are capable of reproducing the set of probe measurements to within 15 percent (although most plots are correct to within 10 percent or less). It is also remarkable that regardless of the method used, the simulated wave always leads the experimental one by two to three seconds. This effect may be due to a lack of synchronism between the pump discharge and flooding of the physical model or also to the numerical inflow boundary condition. It is also remarkable that the trend of the low water depths (about 1 cm) in the wake of the last building (probe number 10 reading) are correctly reproduced by the models.

5. CONCLUSION

An overview of the experimental, modelling and benchmarking programme set up during the course of the IMPACT project as regards flood propagation in urban areas has been presented. As explained in the preceding sections, local flow characteristics around buildings as well as the global picture of a severe flood over a model city are being experimentally investigated. The huge data set obtained is being used to test mathematical models as they are developed and adapted to simulate urban flood conditions. The brief set of results presented in this paper seems encouraging enough to proceed with the programme and apply the modelling techniques to reproduce a real, documented, catastrophic flood event.

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CHAPTER 12

SUSTAINABLE DEVELOPMENT AND FLOOD RISK – REDUCING UNCERTAINTY (BRISTOL CITY RE-DEVELOPMENT CASE STUDY)

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Abstract: Development and Flood Risk has become a topical subject for debate at national, regional and local level by politicians, planners, regulators and those with commercial and legal interests. Current UK planning policy guidance seeks to manage and reduce the impact of flooding by applying a precautionary approach to the land-use planning process and further to take account of climate change. As part of any development proposal there is the need to prepare estimates of flood depth, extent and frequency. In making such predictions much reliance is placed on the application of computational modelling often in circumstances where there is little or no supporting hydrometric data to provide corroboration. The paper illustrates the practical measures that have been taken to reduce the uncertainty associated with an established flood risk impacting an urban redevelopment proposal within a major English conurbation. The strategic collation and enhancement of key datasets, including topographical, hydrological and asset information is presented. Focusing on a significant investment in hydrometric measurement and the creation of a fully hydrodynamic two-dimensional hydraulic model the paper demonstrates the requirement for high quality datasets and the use of appropriate techniques in circumstances where model water level predictions are sensitive to small changes in key parameters. In conclusion consideration is given to how the planning process can encourage the appropriate fiscal and resource investment needed to reduce uncertainty in flood risk assessments

Keywords: flood risk, uncertainty, urban redevelopment, PPG25, hydrometric measurement, two-dimensional hydraulic modelling, TuFlow

Abbreviations: PPG25 Planning Policy Guidance Note 25
TuFlow *Two-dimensional Unsteady Flow*. A computer program for simulating depth-averaged, two and one-dimensional free surface flows as occurs from floods and tides

This paper deals with the reduction of uncertainty in fluvial flood risk mapping. The ideas and opinions expressed are those of the author and not Capita Symonds Ltd.

IFM	Indicative Floodplain Map. As published by the Environment Agency indicating those areas at risk from flooding
NSWI	Northern Storm Water Intercept. Flood diversion channel operated during extreme events to reduce flood risk to Bristol
LiDAR	Light Distance and Ranging
DTM	Digital Terrain Model
FRA	Flood Risk Assessment

1. INTRODUCTION

In the UK national planning guidance on Development and Flood Risk is now given in Planning Policy Guidance Note 25 (DTLR, July 2001) (Office of the Deputy Prime Minister, 2001) which replaces Circular 30/92 (DOE, 1992). Amongst other things the guidance in PPG25 states “Policies in redevelopment plans should outline the consideration which will be given to flood issues, recognising the uncertainties that are inherent in the prediction of flooding and that flood risk is expected to increase as a result of climate change”. It goes on to state that “Planning authorities should apply the precautionary principle to the issue of flood risk, using a risk-based search sequence to avoid such risk where possible and managing it elsewhere”. One of the more innovative and indeed controversial elements of the guidance note is the recognition that those wishing to undertake development that may impact flood risk and urban or surface water drainage must bear some of the cost in determining, quantifying and managing the risk resulting from such development. Indeed it goes as far as saying “Developers should fund the provision and maintenance of flood defences that are required because of the redevelopment”.

The Environment Agency of England and Wales is charged with advising planning authorities on the application of PPG25 which in part it discharges through the creation and publication of maps which indicate areas considered to be at risk from flooding. This national dataset is, and by necessity remains, indicative, the intention being that refinement of the understanding of flood risk be considered more closely at a local level through the planning process. The methods used to derive these indicative maps are based on well understood and standard techniques and are applied through a national specification (Environment Agency, 2003). However, in considering flood risk at a local level, and in particular in circumstances where the assumptions inherent in these techniques are exceeded, there is a need to reduce the uncertainties associated with estimation of flood water levels and flood extents. This is particularly the case in urban environments where the predominance of culverted watercourses, extensive development on the natural flood plain and the interaction of urban drainage systems warrant close scrutiny of the techniques used to determine flood risk.

This paper describes a series of innovative approaches, which have been adopted to reduce the uncertainty associated with the previously identified flood risk at a location in the centre of the City of Bristol, England.

2. FLOOD MAPPING IN ENGLAND AND WALES

In England and Wales The Environment Agency has the lead role in providing advice on flood issues at a strategic level and in relation to planning applications. Under Section 105 of the Water Resources Act (1991), the Agency has a duty to survey matters relating to flooding, including the identification of areas where flood defence problems are likely. Department of the Environment Circular 30/92 (1992) "Development and Flood Risk" (MAFF circular FD1/92), and latterly Planning Policy Guidance Note 25: Development and Flood Risk, provide guidance for all responsible authorities on the use of the maps produced by the Environment Agency in discharging this duty.

In 1994 the Environment Agency's predecessor the National Rivers Authority initiated a £25m programme of floodplain mapping across England and Wales to meet the requirements of the Department of the Environment's Circular 30/92 and Welsh offices Circular 68/92. Projects were established to deliver work for development hotspots identified and agreed in a Technical Protocol with the Local Government Association (LGA). In order to provide more precise information a national programme was adopted by the Environment Agency in 1996 to prepare maps for these priority areas. Following the 1998 Easter floods and government pressure all modelling studies and records of flood events were combined to produce one flood outline. This included work carried out as part of the hotspot studies and was supplemented using data from historical records, local knowledge and a study carried out by the Institute of Hydrology (1996) (Report IoH 130). The combined flood outline was used to produce an Indicative Floodplain Map (IFM). These maps were issued to all planning authorities in England and Wales during 1999 and were published on the Internet in November 2000. By March 2003 studies at 821 'hotspot' locations across England and Wales had been completed and the IFM is updated annually as new information becomes available.

It is important to note that the IFM was produced as a flood awareness tool, not for making site-specific decisions. Despite this and the fact that PPG25 states explicitly that "such assessments do not absolve local planning authorities and developers from making their own assessments of risk when proposing sites for development..." there is mounting evidence that the IFM is not always applied with the purpose to which it was created in mind. The IFM is increasingly used by financial institutions, the insurance industry, in flood warning and emergency planning to supplement their business. Consequently there is a need to be sure of the quality of the information being presented. Indeed the guidelines require local planning authorities to be aware of the realistic limits to accuracy and precision in all predictions of flood events and apply these in determining development proposals.

The methods used to determine flood water levels and flood extents, which underpin the IFM, are well considered and the techniques that must be applied when undertaking hydrological and hydraulic modelling assessments are carefully specified (Environment Agency, 2003). However amongst those specialists who undertake the modelling assessments and work with the outputs there is clear understanding that the techniques applied are by necessity fit for purpose. "Fitness

for Purpose” in this context is that the quality and reliability of the mapping data meets the needs of a flood awareness tool only.

If when considering proposals for development and through the application of the planning guidance it is determined that a more detailed flood risk assessment is warranted the appropriateness of the IFM and the underpinning modelling is called into question. This is of particular relevance in urban areas where it must be asked; do the model outputs appropriately reflect the flood flow mechanisms, which have often been complicated by the impact of urban development on overland flow routes and the interaction with urban drainage systems? Has it been possible to calibrate and verify the model in situations where there is often a lack of hydrometric data, particularly associated with stormwater drainage systems and culverted watercourses? Has the basis of model development been clearly stated and have the limitations in accuracy (spatially and temporally) been tested and demonstrated not to be sensitive to the selection of influential parameters? In conclusion is the level of accuracy sufficient to satisfy those who are responsible for considering the impact of flood risk during urban redevelopment for example?

The problems facing inspectors and assessors when considering flood risk often, particularly in urban areas, relate to the uncertainty over the predictions in flood flows and water levels. Considered alongside other uncertainties such as the potential impact of global climate change it can be seen that non-experts are increasingly uncomfortable with decision making in such circumstances (Dale, 2003). Consequently specialists involved in determining flood risk are incumbent to identify concerns and uncertainties in the hydrological and hydraulic models used and wherever possible reduce these uncertainties to aid decision making.

3. BRISTOL BROADMEAD CASE STUDY

The city of Bristol has long suffered from flooding. There are records of significant flood events of the River Frome in the city of Bristol dating back to the 1700's (British Hydrological Society). Many significant floods have occurred in the 20th century with documented events occurring in 1926, 1935, 1936, 1937, 1960, 1974, 1980, 1982, 1999 and 2000. Flooding in Bristol is not restricted to fluvial flooding. Tidal flooding, deficiencies in surface water drainage systems, and fluvial flooding from the River Avon exacerbates the situation. The focus of this study remains fluvial flooding from the River Frome.

Upstream of Bristol the Frome catchment is dendritic and drains a number of rural and semi-rural sub-catchments. Within the city urban drainage facilities serving the Bristol Area – the Frome culvert system and the Northern Stormwater Interceptor Tunnel – contribute to the management of flood flows in the catchment. The catchment and study area include significant areas of urbanisation, notably Bristol and in recent years there has been extensive development in the lower catchment. Various alleviation measures such as the Tubb's Bottom Reservoir and the Northern Storm Water Intercept (NSWI) have been implemented because of this development and seek to control the magnitude of peak flood flows in the lower

reaches of the Frome. Due to the characteristics of the lower urban reaches and the importance of controlling flows through urban Bristol much previous work has been done on the catchment and river flows of the River Frome. However flood risk remains a concern and common flood affected areas include Eastville, St Paul's and Broadmead. Figure 1 shows in diagrammatic form the lower Frome and River Avon hydraulic system below Tubb's Bottom Reservoir and in relation to the city centre.

In 2002 the Environment Agency completed a study to prepare Indicative flood risk mapping as part of the Agency's commitments noted above. In addition to mapping a length of approximately 46.9km a baseline unsteady ISIS hydraulic model was created and provided design flood return period levels and flows at each mapping river cross-section location.

To create the model and provide best value for money existing hydraulic models and survey information were utilised. The hydraulic model was split into two distinct reaches at Frenchay Weir to optimise run times and as a result of the clients nodal licence limit. A total of 56 inflow hydrographs enter the models, 40 in the model upstream of Frenchay and 16 into the downstream Frenchay model. The downstream boundary condition for the upstream Frenchay model is the rating curve for the Frenchay Gauging station.

Five downstream boundary conditions were used in the downstream Frenchay model since the river Frome culvert system discharges into the Bristol Floating harbour at a number of locations (Frome Culvert, Castle Ditch Culvert, Fosse Way Culvert, and Castle Green Tunnel). At these discharge points head time boundaries with a constant water level of 6.6mAOD were used for the duration of the flood

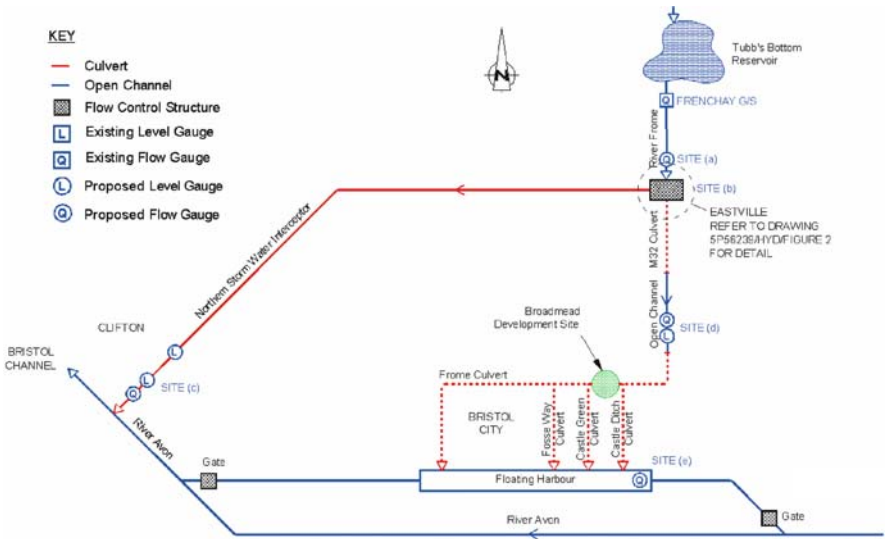


Figure 1. – River Frome hydraulic system upstream of and through Bristol

(Atkins and Partners, 1993). The fifth downstream boundary condition used was a head time boundary representing tidal levels in the River Avon at the NSWI tunnel's discharge location.

The NSWI is part of a scheme instigated in the 1960s to provide flood relief from the Frome to the city centre. The scheme is managed at the Eastville Intake structure, where gates are controlled to divert a proportion of flood flows into the NSWI and away from the Frome as it passes through the city. The arrangement is shown diagrammatically in Figure 2

The outfall structure is tide flapped and subjected to the full range of a spring tide. When the tide flaps close during a rising tide, it is believed that the tunnel can discharge a portion of the flow in a tide locked situation (City and County of Bristol, 1962), the remaining flow being reflected back up through the tunnel as a flood wave. The head time boundary used was based on tidal level data measured at Avonmouth with the assumption that the water gradient or the difference between Avonmouth and the NSWI discharge location water levels was negligible. The

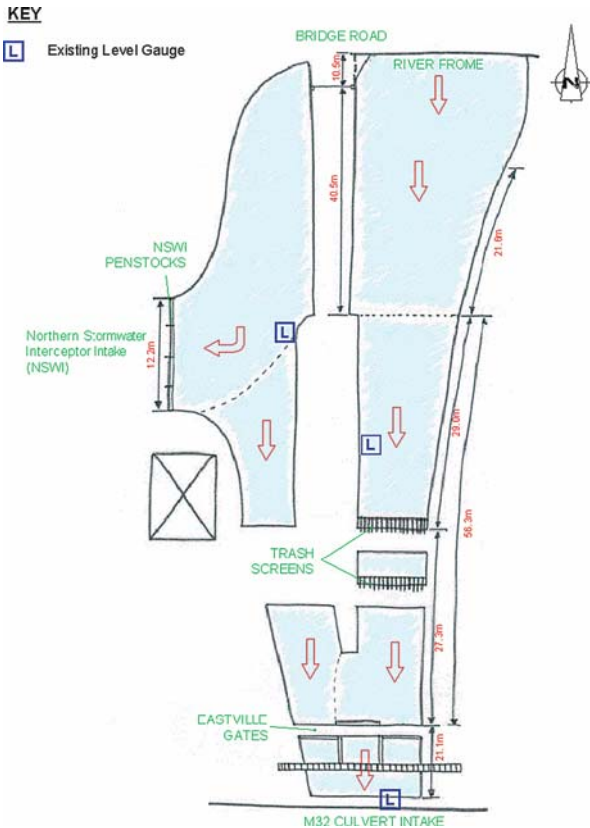


Figure 2. Northern Storm Water Intercept (NSWI) shown diagrammatically

outlet of the NSWI to the River Avon is a complex hydraulic structure that has significant influence on the flow capacity of the upstream tunnel. Assumptions on the hydraulic performance of the structure were made and it was modelled as an orifice unit with tide flaps. A flow abstraction unit was used to simulate discharge during tide locking since the outfall is believed to be able to discharge a portion of flow in these circumstances; this portion is estimated to be 60% (City and County of Bristol, 1962) a maximum abstraction of 50% was used in the hydraulic modelling. The NSWI intake at Eastville, which consists of four automated vertical sluice gates, was simulated in the model using vertical sluice gate control options. Once all four gates are opened the water level is self determined.

A number of assumptions were made during the construction of the model which although acceptable for the production of indicative flood risk mapping, were highlighted in the supporting documentation. Flood return period water levels were produced for the 100, 50, 20, 10, 5 and 2-year events and flood mapping produced in accordance with the Environment Agency specification (Environment Agency, 2003).

4. BROADMEAD DEVELOPMENT

In August 2002, the Environment Agency was consulted on a planning application submitted to the Planning Authority relating to the redevelopment for mixed retail, office, residential, public open space and access alterations to the highway network at land bounded by Newfoundland Street, Penn Street, Houlton Street, Wellington Road, Castlemead and Bond Street Bristol, principally the area known as Broadmead. In part because of the results of the IFM study, the Environment Agency advised that the redevelopment area was affected by extreme fluvial flows in the River Frome and tidal events from the River Avon.

Symonds Group was commissioned by the development proposer to undertake a Flood Risk Assessment (FRA) for the urban redevelopment proposal. The flood risk assessment was undertaken in accordance with the guidance given in planning Policy Guidance Note 25 – PPG25 (DTLR, July 2001). Much of the FRA utilised the work that Symonds had previously undertaken on behalf of the Environment Agency. The FRA recognised that the fluvial flood risk was very much dependent on the operation of the control structure at Eastville and the performance of the culverted sections within the study area. The assessment recognised the assumptions made in the previous modelling exercise and consequently the limitations of the results. Importantly it was acknowledged that in order to reduce the level of uncertainty there was a need to collect additional flow and level data to better understand the influential flow mechanisms at the control structures. There was also a recognition that the currency of survey information, the availability of topographic information through the urban area and crucially the assumptions made at the downstream boundaries added to the uncertainty of the modelled flood risk. As a consequence of the flood risk assessment in October 2002 the Environment Agency advised on conditions that should be attached to the outline permission. Of note the conditions included for the need for a more detailed flood risk assessment to be completed

which should incorporate further data to refine the existing hydraulic model. The key issue being that sensitivity testing of the existing model at Eastville revealed that small changes in flow magnitudes generated large fluctuations in water level, which was exacerbated by the significant influence of tidal levels in the Avon on water levels at Eastville – hence the high level of uncertainty associated with flood risk in the lower Frome.

The developer therefore appointed Symonds to undertake a variety of works to reduce the uncertainties associated with flood risk in the development area so that the reserved matters of the planning application could be met. Broadly speaking these works have been:

- Installation of flow and level measurement at key locations.
- Data collection over a winter period to more clearly understand the operation of flood defence structures in the system and provide calibration information.
- Collection of additional topographic datasets to characterise the urban area.
- Collection of additional datasets with which to model the interaction of surface flows and sub-surface drainage systems.
- Detailed computational modelling to more clearly define the flood risk resulting from overland flows, surface and sub-surface flow interactions and the operation of the culverted sections of watercourse.

5. DATA COLLECTION

The ISIS model made use of river survey data from existing models that are over 10 years old. Information on the Frome culvert system was originally collected by WS Atkins in the early 1980s (Atkins and Partners, 1982). Although some new information was collected during the construction of the ISIS model the first step of the detailed flood risk assessment was to quality assure topographic information through an independent check survey. Previously, many of the drainage and culvert systems throughout the lower model were either excluded from the model or based on uncertain information. Of particular concern was the absence of information with which to classify terrain in the heavily urbanised areas.

To support the new hydraulic modelling and to provide more detailed information of the urban topography it was decided to use LiDAR (Light Distance and Ranging) information provided by the Environment Agency. The LiDAR dataset made it is possible to characterise the large urban area of the study where traditional surveying techniques would have been cost prohibitive. This is particularly important in instances where the built environment exerts significant influence on the progression of the flood hydrograph and consequently propagation of flood levels. The information collected by airborne sensors can produce high resolution and accurate height information with ground resolutions of 1–2m and height accuracies of 15–25cm. From this information a Digital Terrain Model (DTM) was constructed. Figure 3 is an example of the DTM created to support the new study.

This was supplemented and checked against survey datasets collected by traditional methods. Comparisons with manhole cover levels obtained from Wessex

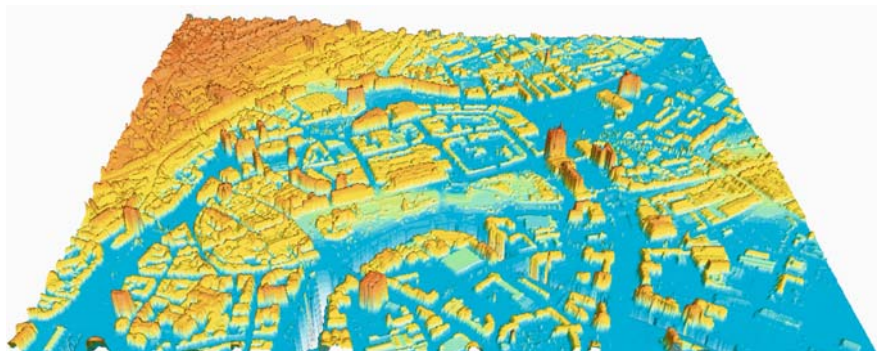


Figure 3. Digital Terrain Model of the Lower Frome centred on the proposed redevelopment area (N.B. The course of the River Frome is culverted throughout the area covered by the image)

Water and with the Ordnance Survey's Master Map Landline dataset were also made to quality assure the DTM.

Details of major subsurface drainage systems including routes, chamber depths, cross-section details and manhole details were also obtained from Wessex Water. These were digitised and geo-referenced to be included as 1-dimensional (1D) elements in the subsequent hydraulic modelling.

In the original ISIS hydraulic model assumptions had to be made at the boundaries of the hydraulic model with little or no supporting data for corroboration. The constant level set in the floating harbour was based on operational information at sluice gates connecting it to the River Avon. Sensitivity testing found the model was sensitive to the head boundaries with increased boundaries reducing the hydraulic gradient and hence potential to discharge floodwaters into the harbour. Consequently there was an increase in flooding in the Eastville to St Paul's reach of the Frome i.e. the proposed development area. Additional sensitivity tests were undertaken to investigate tide locking of the NSWI outfall. Variations in the abstraction percentage (simulating the continued discharge of the NSWI during tide locking), the opening of the NSWI penstock gates threshold and the timing of the River Avon spring tide were also tested. Perhaps not surprisingly, significant deviations from the baseline ISIS model were found when the timing of the spring tide was altered and the efficiency of the NSWI outfall varied. It was concluded that changes in flow had a profound influence on flooding in the lower Frome. The lack of hydrometric information to test the modelling assumptions was therefore a concern for the detailed FRA also. It was particularly important in the detailed FRM to have available hydrometric data for calibration purposes also. Although calibration was possible for a limited number of events in the upper catchment ISIS model, downstream of Frenchay Weir there was no data available for this to occur - yet this is where the greatest implications for flood risk are found. In view of the influential significance of the flood defence structures and the lack of calibration in the lower ISIS model the detailed FRA put in place a programme to collect additional data.

Table 1. Summary details of hydrometric measurement installed as part of the detailed flood risk assessment

National Grid Reference (Site name)	Location	Installation purpose	Instrumentation
ST 563 741 (Black Rock)	Discharge point of the NSWI to the river Avon.	To determine the efficiency of discharge from the NSWI during tide locking.	Two Doppler ultrasonic flow meters with integral pressure level sensors
ST 597 736 (Wade Street.)	Immediately upstream of the entrance to the river Frome Culvert in the vicinity of the proposed development	To determine flood flows entering the river Frome culvert system and to confirm the estimated flows passing through the Eastville complex. To provide information for model calibration.	A multi-path time-of-flight ultrasonic flow gauge. 3 paths set in an in line configuration. Level measurement via pressure sensor and upward looking ultrasonic level device.
ST 594 729 (St Phillips Bridge)	Within the floating harbour	To determine water level for model downstream boundary and to provide information for model calibration.	An air-vented pressure sensor set within a stilling chamber.
ST 603 749 (Glenfrome Road)	Within the NSWI just downstream of the control gates within the Eastville flood defence complex	To determine head difference (with the Black Rock installation) in the NSWI and provide information for model calibration.	Two air-vented pressure sensors set in conduits within the NSWI.

This data would test the NSWI tunnel's ability to discharge flows to the Avon during extreme events and provide further confidence in the new computational hydraulic model through calibration. Table II summarises the location, purpose and instrumentation deployed to collect this additional information.

The aims of the regime were to collect information over one winter season in a robust and yet cost effective way. Figure II includes the locations at which the instrumentation was installed. Use has also been made of level data measured for the operation of the flood defence structures in the Eastville compound by the Environment Agency. Although not routinely archived a procedure was set up so that the data was recorded for the purposes of the flood risk assessment. The structures within the Eastville compound, which are non-standard, would not provide an easy method from which to derive flow from level. It was therefore decided to measure flow directly within the NSWI as detailed in Table II. Consequently two Doppler ultrasonic devices were installed within the NSWI. The site chosen was determined by ease of access to the culvert. It was fortunate that the access chamber just upstream of the culvert's discharge point at Black Rock enabled the measurement of both fluvial flows from the NSWI and tidal flows resulting from insurgence past the gravity gates during a high tide. At each installation data is continuously logged at 15-minute intervals, collected, quality controlled and archived. The installations have been installed and the data is collected in line with the relevant British and International Standards (BS 3680 Part 3E (ISO6416), 1992; ISO/TS 15769, 2000).

The hydrometric installations were designed, specified, procured and installed as part of the flood risk assessment, the costs being met by the redevelopment

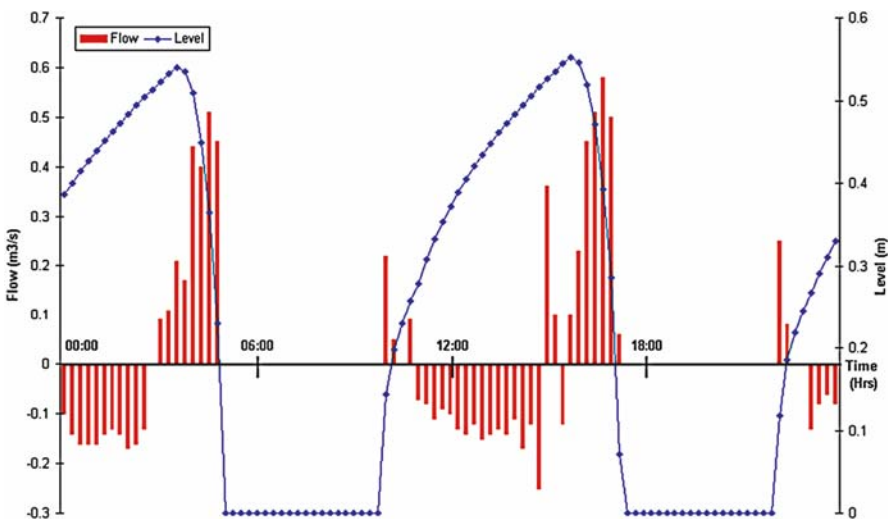


Figure 4. Example flow and level data within the NSWI captured over a one-day period. (N.B. information is from one of two Doppler ultrasonics deployed and so represents a proportion of the total flow)

proposer. Data collection began during September 2003 with the intention that data will be collected for a complete winter season. Figure 4 shows an example of flow and level data that has been collected at the Black Rock site.

6. HYDRAULIC MODELLING

The indicative flood maps (IFM) were constructed using a traditional dot-to-dot method. This involved the calculation of offsets determined directly within the ISIS hydraulic model where the modelled water surface intersects ground level beyond the channel bank and plotting these points on a scale map. The points are then joined together by hand using available topographic information (5m interval contours) and engineering judgement to decide what happens between cross sections. The interconnecting plotted lines are then digitised within ArcView to produce the flood outlines. Where the flood level exceeds the elevation of the original cross section the cross sections are extended using landline contour data. This results in a less accurate method of determining the ground elevation at the point of intersection and was found to be particularly constraining in urban areas. Where there are levees or complex flood flow paths, engineering judgement is required to assess the flow in the creation of the IFM. In urban areas ground levels typically vary greatly over small distances and the built environment, channel walls, buildings, road and hard surfaces etc heavily influence the topography creating particular difficulties. So as to provide some ground truth to the flood plain maps derived, flood incident reports and anecdotal evidence illustrating the extent of inundation during recent floods were also considered. It was not possible to prepare flood risk mapping for the lower reaches of the culverted sections of the River Frome leading into the Floating Harbour. It was accepted that the flooding in this area would require more detailed consideration of the interaction of the watercourse, stormwater sewers and other urban drainage systems, together with an assessment of overland flow paths downstream of the entrance to the Frome culvert. Once channel capacity was exceeded by the 100-year event at this and other points no assessment was made of the flow paths outside of the watercourse. The impact of this on the detailed FRA was considered paramount since inundation of the proposed development area may result.

One of the key weaknesses of the S105 study undertaken therefore was the inability to hydraulically model out of bank flood flows through the lower reaches of the River Frome, where the characteristics of the built environment dominate flood risk. The interaction between channelled flood flows, over land flows and sub-surface drainage was also of key concern and not accounted for in the ISIS modelling exercise. It is particularly challenging therefore to derive flood flow and level estimates for urban and suburban areas as they typically show the following characteristics:

- Complex flow routes and levels through the built environment
- The presence of discrete lengths of flood defences

- Interaction between sub-surface water systems and river flows and
- Heavily engineered channels and loss of functional flood plain.

The study area is characterised by many of these features as is shown in Figure 5.

The benefits of 2D modelling of flood risk are noticeably realised in the urban environment where there are demands that estimates are made of the flood hazard and the consequences in addition to flood extent. In this regard it is not only the frequency of flooding that is influential but also the depth, duration, velocity and extent. Fully hydrodynamic 2D models are capable of furnishing greater information on these parameters and can deliver the required strategic information. The benefits that will be accrued through the use of 2D fully hydrodynamic models in the urban environment can be summarised thus:

- The improved analysis of flood plain (out of bank) flows via better definition of physical situations and hence improved accuracy and confidence in results
- The improved identification and representation of surface water reflected flooding
- The improved prediction of flood hazards i.e. depths of flow velocities and durations and
- The improved representation of fluvial/tidal interaction.

For the purposes of the detailed flood risk assessment it was therefore decided to construct a fully two-dimensional hydrodynamic model to overcome these limitations. The modelling package chosen was TuFlow. TuFlow (*Two-dimensional Unsteady Flow*) solves the full two-dimensional depth averaged momentum and continuity equations for free surface flow. It also incorporates the full functionality of the ESTRY one-dimensional (1D) network solving the full (1D) free surface flow equations. The initial development of TuFlow was carried out as a joint research and development project between WBM Oceanics Australia and the



Figure 5. Open channel section of River Frome (downstream of the M32 culvert and immediately upstream of the Frome culvert) illustrating key features of an urban watercourse

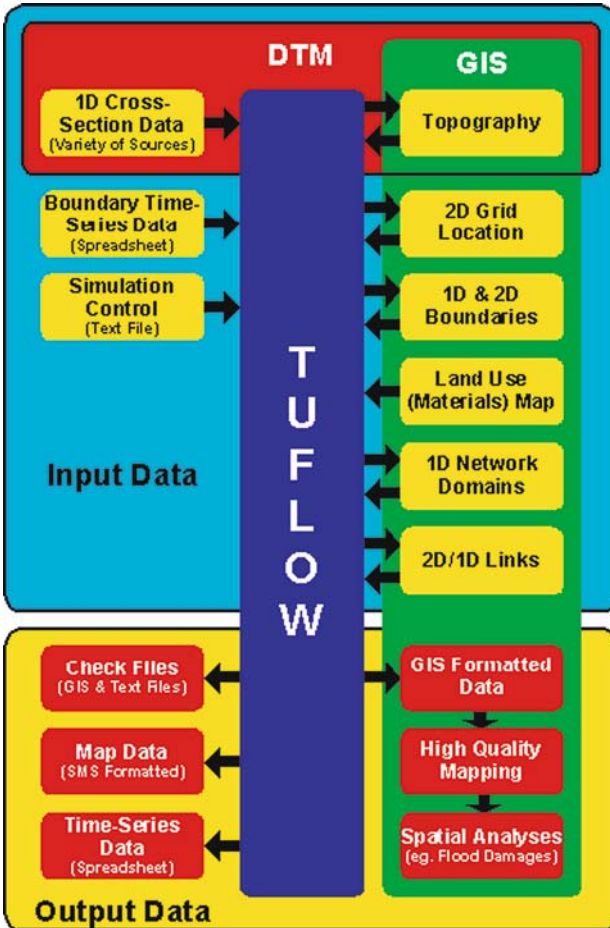


Figure 6. TuFlow input and output structure (reproduced with permission of WBM Oceanics Australia)

University of Queensland in 1990. The project successfully developed a 2D/1D dynamically linked modelling system and latterly incorporated improvements in modelling hydraulic structures, advancing 1D/2D linking and using GIS for data management. TuFlow is specifically orientated towards establishing flow patterns in coastal waters, estuaries, rivers, flood plains and urban areas where the flow patterns are essentially 2D in nature and cannot, or would be awkward to represent using a 1D network model. A powerful feature of TuFlow is its ability to dynamically link to 1D networks. The user sets up a model as a combination of 1D network domains linked to 2D domains.

The TuFlow and ESTRY computational engines utilise GIS and other software for the creation, manipulation and viewing of data. Principally these are a GIS (e.g. MapInfo); 3D surface modelling software running inside the GIS (e.g. Vertical

Mapper) for the creation and interrogation of a DTM and for creating 3D surfaces of water levels, depths and hazards; SMS (Surface Modelling System) for the viewing of results and creation of flow animations; and a text editor and spreadsheet software for data manipulation. The blend of these readily available tools provides a powerful, economical, combination of software for hydraulic modelling.

Figure 6 illustrates the data input and output structure required to create a TuFlow model.

Text files are used for controlling simulations and simulation parameters, whilst the bulk of the data input is in GIS formats. A GIS system is used to set up, modify, thematically map and manage the data. The required datasets include the digital terrain model, a materials layer in which hydraulic roughness is determined, breaklines or lines of elevation that may impact flow paths in the 2D domain (e.g. flood defence structures) and 1D elements such as open channel or sub-surface drainage networks.

Once constructed the baseline TuFlow model was run. The upstream boundary condition to the 2D model was an inflow hydrograph derived from the lower ISIS model at the point at which the modelled areas coincided (at the entrance to the River Frome Culvert). This approach was taken so as to make best use of the previous study and to minimise the extent of the 2D domain, and so run times. The lower catchment ISIS model also incorporated the operation of the Eastville compound and NSWI. It is anticipated that during the course of the flood risk assessment this will allow alterations to the lower ISIS model, based on the additional hydrometric data collected, to be made, to account for the actual operational efficiency of the flood defence structure and as a consequence the shape and size of the hydrograph entering the 2D domain.

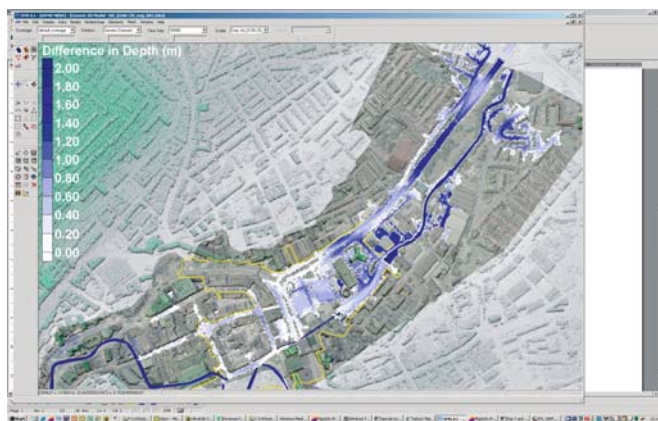


Figure 7. Example output from 2D hydrodynamic model. Depth (m) resulting from 100 year return period flood (plus 20% for sensitivity) throughout the study area



Figure 8. Example output from 2D hydrodynamic model. Difference in depth (m) before and after proposed development for 100 year return period flood (plus 20% for sensitivity)

Outputs of water level, depth, flow direction and velocities were obtained from the 2D model for a number of scenarios. Figure 7 shows modelled water depths from the baseline 1 in 100 year flow (plus 20% for sensitivity) flow model for the study area. Subsequently the baseline model was amended to include the topography of the proposed redevelopment. Figure 8 shows a comparison of the modelled water levels before and post development for the same event.

From these results it was possible to demonstrate not only the baseline conditions in terms of flood extent, flow routes and velocities but also the consequence of the proposed development. As part of the flood risk assessment ongoing studies are investigating mitigation methods through the incorporation of additional storage, culverted and surface flow routes and building thresholds and floor levels.

7. CONCLUSIONS

A number of drivers are changing the needs for flood plain mapping and flood risk assessment (BS 3680 Part 3E (ISO6416), 1992). The publication of PPG25 in July 2001 led to a major change in the way local planning authorities (LPAs) consider flood risk as part of the Town and Country Planning process. Additionally other organisations (financial planning services and insurance bodies) are increasingly using flood risk information. There is therefore a fundamental need to recognise the limitations and uncertainties of the (mapped) data that is available to such organisations and where required there must be amendment and improvement of the techniques which underpin these studies. The planning system now offers opportunity to realise these objectives.

In the built environment in particular it is essential that the model and techniques adopted for the study are fit for purpose. The model selected must accurately reflect

the flow/flood mechanisms; be calibrated and verified wherever possible and must demonstrate that it is not sensitive to the selection of influential parameters.

In conclusion it is incumbent upon specialists in the field of flood risk and flood mapping to identify concerns and uncertainties in the hydrological and hydraulic models used. Whenever required these uncertainties must be reduced through the application of the most appropriate techniques available together with the collection of good quality hydrometric and supporting information. In doing so considerable assistance will have been given to those required to make decisions where flood risk is an issue.

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CHAPTER 13

FLOOD RISK MAPPING AT THE LOCAL SCALE: CONCEPTS AND CHALLENGES

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Abstract: Maps give a more direct and stronger impression of the spatial distribution of the flood risk than other forms of presentation (verbal description, diagrams). Thus, maps are valuable for presenting and assessing the local flood situation, and they provide information for many applications in flood defence and disaster management. In Europe, there are no standardised nomenclature or agreed practices for flood mapping. The paper reviews the concepts of flood risk mapping at the local scale, discusses the challenges and proposes a systematic presentation of flood hazards, vulnerabilities and flood risks, spanning from flood danger maps to damage risk maps

Keywords: flood hazard, vulnerability, risk, flood mapping

1. INTRODUCTION

Widespread flooding with dramatic damages in Central Europe in August 2002 have again shown the importance of flood risk management. One of the cornerstones of flood risk management is the information of people at risk and of the authorities and agencies responsible for flood management. Only if the people and decision makers are aware of the flood risk, and only if they are able to evaluate the risk, they can be expected to adequately respond to this threat. The basis of effective and efficient risk reduction measures are risk analyses which take into account the different aspects of the flood risk, e.g. hydrological, hydraulic, economic, social

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and ecological aspects. To communicate the results of risk analyses and to sensitise people at risk and decision makers, the spatial description of the risk plays an important role.

The flood risk may be described at different scales, ranging from the global to the local scale. Examples for approaches at the global scale are the analyses of [Lehner & Döl, \(2001\)](#) with maps concerning the flood situation in Europe under climate change, and the world map of natural hazards ([Berz et al, 2001](#)), showing, among others, areas threatened by floods due to storm surges and severe rainfall. Most flood risk mapping approaches concern the local scale. Such maps allow to assess the flood situation for single land parcels and objects like buildings and infrastructure. They are the basis for local flood defence measures. Usually, maps at the local scale have a scale of 1:2000 to 1:20000.

Hitherto, there are different approaches for flood risk mapping. Table [1](#) compares flood mapping procedures in Italy, Norway and Spain and exemplarily shows the heterogeneity of flood mapping in Europe. In many countries, e.g. United Kingdom, Germany, Spain, France, USA, Canada and New Zealand, the area affected by a 100-year flood plays an essential role for flood mitigation ([Marcd, 1994](#), [Wat, 2000](#)). As a consequence of the floods in 2002, some federal states in Germany have accelerated the activities for flood mapping. They use the 100-year flooded area as representation of the flood hazard. Additionally, some states identify (a) the area which would be flooded for the 100-year scenario if the flood defence failed, and/or (b) flood areas for larger return periods, e.g. 200-year flood.

Some countries have adopted nation-wide initiatives for flood risk mapping. For example, the UK Environment Agency currently offers the 'Indicative Floodplain Map' for England and Wales online. In summer 2003, the agency produced a flood mapping strategy initiating a five-year programme of further flood mapping work, which will improve and increase information on flood risk over time ([Environment Agency, 2004](#)). In the Netherlands, the long-term project FLORIS (Flood Risk and Safety in The Netherlands) aims at estimating and mapping the probabilities and consequences of flooding for all 53 dike rings in The Netherlands ([TAW, 2004](#)).

In Spain, planning of flood areas is included in the Water Act and some of its regulations ([Menendez, 2000](#)). There are four zones, for which restriction in land use are given: the "channel" (10-year flood zone), a restricted-use area, i.e. a five meter buffer on either side of the channel, a surveillance zone, i.e. a 100 m wide strip on either side of the channel and a flood risk zone, i.e. theoretical levels during floods with a return period of 500 years. In the first three zones authorisation is required for any kind of construction.

Switzerland heavily engages in mapping activities to identify zones which are prone to natural hazards ([BUWA, 1998](#)). The cantons are obliged to provide hazard maps and to consider these maps in land-use planning ([BWW-BRP-BUWA, 1997](#)). These maps contain information about the intensity of a dangerous process and about its exceedance probability. The intensity and the exceedance probability are combined to quantify the hazard, expressed in hazard levels. Figure [1](#) shows the intensity-probability matrix and the different hazard levels. By means of this matrix,

Table 1. Examples how flood mapping is regulated and harmonized in different European countries (T: Return period in years)

	Italy	Norway	Spain
Frame	Methodology for flood risk mapping was introduced by law 180/1998.	Norwegian flood inundation map project, initiated by the Norwegian Water Resources and Energy Directorate in 1995	Water Act and some of its regulations; Basic Criteria on Civil Protection
Reason/trigger	Devastating landslide in Sarno, near Napoli in May 1998	Major floods in South Eastern Norway in 1995	*
Hazard	3 classes: high: T = 20–50a moderate: T=100–200a low: T=300–500a	Inundation maps for the 10-, 20-, 50-, 100-, 200- and 500-year flood (1750 km river length)	Flood plain zonification (Basic Criteria on Civil Protection): frequent flood zone: T = 50a occasional flood zone: T = 100a exceptional flood zone: T = 500a In some regions, e.g. in Valencia, these zones are altered with additional information about inundation depths or velocities.
Vulnerability	Degree of exposure to hazard on a scale from 0 to 1, and value	Exposure	*
Risk	4 categories (qualitative)	–	*
End-user, scale	*	Local municipalities, 1:15000	*
Technical guidelines	*	Yes	*
Source	Borga (pers. communication)	Hoydal et al. (2000)	Menéndez (2000)

* no information available

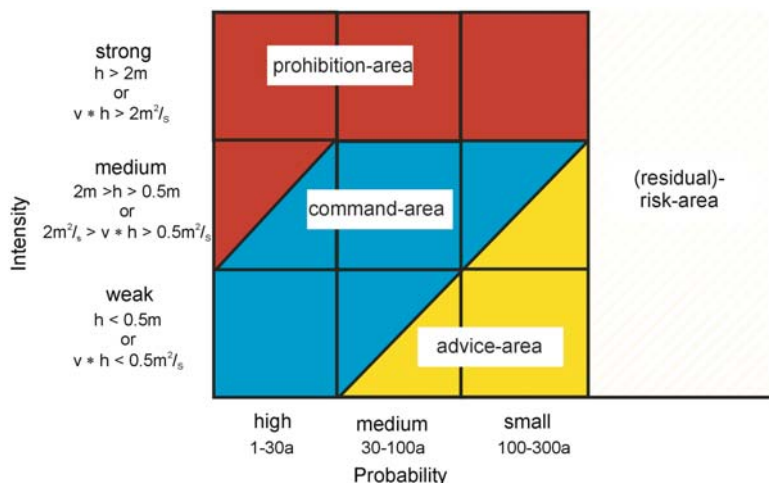


Figure 1. Intensity-probability-matrix for the assessment of hazard-prone areas (danger zones) as basis for land-use planning in Switzerland (modified from [BUWAL, 1998](#)). In prohibition areas construction is generally not allowed. In command areas construction is allowed under certain restrictions. In advice areas construction is possible, but recommendations are given. The (residual)-risk zones cover areas where natural processes might occur but with a very small likelihood. Sensitive objects, e.g. schools, should not be built in such zones

areas are characterized as zones of land-use bans, restrictions and recommendations. These zones are the basis for land-use planning.

In 2001 the International Commission for the Protection of the Rhine ([ICPR, 2001](#)) published the Rhine-Atlas which is available on the internet (<http://www.rheinatlas.de/>). The Rhine-Atlas has a scale of 1:100000 and gives an overview of the flood situation for the 10-year, the 100-year and an extreme event. It has to be noted that the Rhine-Atlas goes beyond the usual flood mapping approaches since it provides (a) cross-border maps, including Switzerland, France, Germany and The Netherlands, (b) an extreme flood scenario, much larger than the 100-year flood, and (c) information about potential economic losses for the extreme flood scenario.

Most flood mapping approaches that include information about flood losses are limited to economic damages. Other loss types, e.g. damage to people or the environment, are seldom mapped. One of the rare examples is provided by ([Jonkman et al., 2003](#)), who estimated and mapped the annual individual risk for loss of life due to drowning for a polder in The Netherlands.

This overview shows that most of the flood mapping approaches are limited to identify flooded areas for certain flood scenarios, mainly the 100-year flood. In some cases additional information about the intensity of the process, e.g. the water depth, is given. Maps that illustrate possible consequences of inundations or information that helps to mitigate flood damages are rare.

Globally, regionally (e.g. in Europe) and sometimes even nationally (e.g. in Germany), there are no standardised nomenclature or agreed practices for flood mapping. This paper reviews the concepts of flood risk mapping at the local scale, discusses the challenges and proposes a systematic presentation of flood hazards and flood risks, spanning from flood hazard maps to damage risk maps.

2. FLOOD RISK – DEFINITIONS AND INDICATORS

The term risk has different meanings. Therefore it is necessary to define it and to give indicators which allow to quantitatively describe and to map flood risks.

In the last decades methods for risk assessment have been developed in different fields, e.g. in the insurance sector and in the fields of environmental or technological risks (Molai, 1997). Here, risk is defined as the probability of suffering harm or loss, and risk analysis is a body of knowledge that evaluates and derives the probability of the adverse effects of a natural process, technology, industrial process or an agent (chemical, physical, etc.). With regard to natural disasters, risk is more specifically described as the probability that natural events of a given magnitude and a given loss will occur. Therefore, risk encompasses two aspects: hazard and vulnerability (Kaplan & Garrick, 1981, Mileti, 1999).

2.1. Flood Hazard

Flood hazard is defined as the exceedance probability of potentially damaging flood situations in a given area and within a specified period of time. An example of a flood hazard statement is the flood frequency curve at a discharge gauge, giving different discharges and their associated exceedance probability. Flood hazard statements do not convey information about the consequences of such floods on society, built environment or natural environment. Since these consequences depend, among others, on the intensity of the flood, flood hazard statements should quantify the intensity of the process that go beyond a flood frequency curve.

The most prevalent indicator for the intensity of a flood is the inundation depth. Different studies identified the water depth as the flood characteristic which has the biggest influence on flood damage (Penning-Rowsell et al., 1994, Wind et al., 1999). Therefore, the discharges from a flood frequency curve are commonly transformed into inundation scenarios (Figure 2).

Another important criterion for the flood intensity is flow velocity. Especially floods in mountainous areas may have high flow velocities which can lead to dramatic damages to buildings, infrastructure etc. For example, in the Ore Mountains in August 2002 high flow velocities completely destroyed many buildings. Further, damage to humans increases with velocity: Persons may be swept away when flow velocities are above 0.5 m/s (Marcd, 1994). However, a better indicator for human instability in flood situations is the product of flow velocity v and water depth h . Abt et al. (1989) made experiments in a test flume on human subjects standing on various surfaces in various depths and velocities until the point of instability was found.

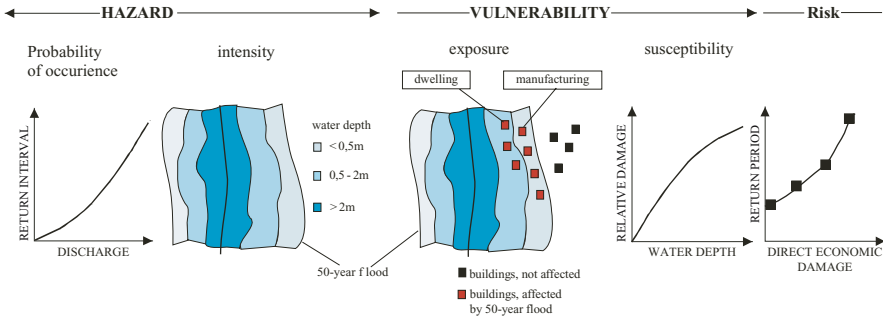


Figure 2. Flood risk as interaction of hazard (exceedance probability and intensity) and vulnerability (exposure and susceptibility)

The critical product hv ranged from 0.7 to 2.0 m²/s depending on the body weight. In Switzerland the product hv is used to classify flood hazard intensity (Figure 1). Usually, flood hazard maps do not contain information about flow velocity. The main reason is the large effort for the calculation of the spatial distribution of velocities. To this end, 2-dimensional hydrodynamic models are necessary which have large requirements concerning data, CPU time and calibration.

Other indicators for flood intensity are the duration of the flood situation and the rate of the water rise. Some systems can bear inundation for a certain time without much damage, e.g. flood plain ecosystems or some agricultural areas. In many cases failure of river levees is also influenced by the duration of the flood water level. The rate of the water rise determines the time that is available for flood defence measures in case of a flood warning. Similar to flow velocity, the consideration of flood duration or rate of water rise necessitates a larger effort. Hydrological simulation models are needed which calculate the rise and fall of the flood wave.

Further flood characteristics that may influence the extent of the damage are the concentration and size of sediment and other transported material like driftwood, or the pollution load of flood waters. For example, the flood-induced contamination with heating oil may lead to complete damage of inundated buildings. These characteristics are rarely shown on flood maps since the quantification of the spatial and temporal distribution of such characteristics dramatically increases the requirements on data and models. In addition, it is questionable how far scenarios can be calculated which would be representative for future contamination situations. This may be possible for particular installations with high damage potential, e.g. oil refinery, chemical facility. For many small, and frequently unknown potential sources of pollutants, e.g. oil tanks in private houses or fuel tanks, it may not be possible to predict the release and transport of pollutants.

2.2. Flood Vulnerability

Besides the flood hazard, the analysis of flood risk involves the characteristics of the elements at risk. The term 'elements at risk' includes all elements of the

human system, the built environment and the natural environment that are at risk of flooding in a given area. Such elements are the population, buildings and civil engineering works, economic activities, ecosystems etc. They experience adverse consequences like fatalities, injuries or psychological stress, destruction of buildings and inventory, interruption of traffic or business and pollution of soils, respectively.

The extent of flood damage depends not only on the flood characteristics but also on the vulnerability of the inundated area. For the same flood, in terms of intensity and exceedance probability, a more vulnerable area experiences higher flood damages.

There are different concepts of vulnerability and there is no agreed understanding of this term (Blaikie et al., 1994; Comfort et al., 1999; Mileti, 1999; Smith, 2001). For example, Blaikie et al. (1994) analysed the complex socio-economic conditions that create a high degree of vulnerability. Access to resources is often the most critical factor in either achieving a secure livelihood or recovering effectively from disaster.

In this paper we apply a narrower definition: Vulnerability is composed of two elements, exposure (or damage potential) and (loss) susceptibility. Exposure analysis answers the question “Who or what will be affected by floods?”. Exposure can be quantified by the number or the value of elements which are at risk. If we look at the building stock in a flood-prone city for the 50-year flood, the exposure may be quantified by the total assets of all buildings within the 50-year inundation area (Figure 2). Analysis of susceptibility answers the question “How will the affected elements be damaged?”.

Due to the manifold types of flood damages, the concept of vulnerability used in this paper can only be discussed exemplarily. The assessment of direct economic damages to buildings due to inundation serves as an example and is outlined in Figure 2. For a given flood situation all inundated buildings are classified according to their use. A typical classification scheme is the differentiation according to economic sectors like ‘private dwelling’, ‘public infrastructure’ or ‘manufacturing’ (Wind et al., 1999; Merz et al., 2004). Typical values for the assets of these economic sectors are derived from statistical data (national, regional or communal statistics, insurance data etc.), yielding for example unit values per economic sector [€/m²].

Susceptibility is usually described by relative damage functions. Such functions give the degree of damage if the building is flooded. Most damage models have in common that the direct monetary damage is estimated depending on the use of the building and the inundation depth (Wind et al., 1999; NRC, 2000). This concept is supported by the observation of Grigg and Helweg, (1973) “that houses of one type had similar depth-damage curves regardless of actual value”. Such depth-damage functions are seen as the essential components upon which flood damage assessments are based and they are internationally accepted as the standard approach to assessing urban flood damage (Smith, 1994).

It is however clear that the direct economic damage to an inundated building does not only depend on the water depth and building use (Smith, 1994; Penning-Rowsell et al., 1994; USACE, 1996; Merz et al., 2004). Other important factors are characteristics of the building (susceptibility of building fabric, precautionary

construction measures etc.), socio-economic variables (flood knowledge, financial status of building owner, age profile of the inhabitants/tenants etc.) and the quality of the emergency response (operational use of early warning systems, time taken for assistance to arrive, amount and quality of response etc.).

The situation is even more complex when other types of flood damage (fatalities, indirect economic damage etc.) are analysed. Therefore, flood damage assessments are frequently limited to direct economic losses. This limitation is problematic since different damage indicators may lead to different conclusions concerning the flood risk. Flood risk might be evaluated as more severe if the flood risk analysis not only considers direct economic damage but also takes into account the adverse consequences on the population and on long-term economic activities in the flood-prone area.

2.3. Flood Risk

In this paper we follow the risk definition that has found widespread use in the insurance sector and in the fields of environmental or technological risks (Molai, 1997). We define flood risk as the probability that floods of a given intensity and a given loss will occur in a certain area within a specified time period. In this way, risk always implies a quantitative measure. As shown in Figure 2, risk results from the interaction of hazard and vulnerability. A certain risk level can be reduced by decreasing the

- hazard, e.g. increase in the water retention capacity of the catchment,
- vulnerability, e.g. reduction of the assets in the flood plain, or installation of a flood warning system.

Risk can be quantified as the expectation $E\langle D \rangle$ of the damage:

$$(1) \quad R = E\langle D \rangle = \int D f_D(D) dD$$

with D as the random variable damage with density function $f_D(D)$. Usually, $f_D(D)$ is expressed on an annual basis, and risk has the same unit as the damage indicator related to the annual time interval (e.g. annual number of fatalities, annual flood damage in €).

In hydrology the term risk is frequently limited to the characterisation of the hazard. For example, Chow et al. (1988) define hydrological risk as the probability that within the expected lifetime n [in years] of civil engineering works a discharge Q occurs that is higher than the design discharge Q_D :

$$(2) \quad R = 1 - [1 - P(Q > Q_D)]^n$$

This definition of risk does not include the vulnerability and does not give any information on the flood damages. Recently, the term damage risk has been used (ICPR, 2001). This term makes clear that risk is more than probability. Therefore, it helps to avoid misunderstandings, and we use it in this paper.

Although we define the term risk in a broader sense than it is usually done in hydrology, our definition does not reflect the numerous aspects of risk that can be found in social sciences. Social scientists often criticize that technical risk analyses do not take into account the multidimensionality and variety of the different views on risk (e.g. [Pidgeon et al., 1992](#), [Blackie et al., 1994](#), [Slovid, 1998](#)). For example, the quantification of risk as damage expectation (equation 1) may not be a suitable risk indicator. This approach does not consider that society frequently tries to avoid situations with dramatic losses ('low probability/high damage-risk'), even though such situations may have very small exceedance probabilities and the damage expectation may be smaller than situations with 'high probability/low damage'-risks. Risk measures have been proposed that consider this societal aversion against situations with dramatic consequences ([Bohnenblust & Slovid, 1998](#), [Jonkman et al., 2003](#)).

3. PROPOSAL FOR SYSTEMATIC FLOOD MAPPING

There are a variety of concepts used for flood mapping and the term 'flood risk map' can have very different meanings. On the base of the definitions given in section 2, the paper proposes a systematic concept for flood mapping, and it discusses the use and challenges of these maps at the local scale. The proposed types of maps are shown in Table 2.

3.1. Flood Hazard Mapping

A *flood hazard map* illustrates the flood hazard, i.e. the intensity of flood situations and their associated exceedance probability. Usually, flood hazard maps show synthetic events. The most simple example is the inundation area for a scenario with a certain return period. Often, flood intensity is given by the spatial distribution of the water depth. In some cases additional information concerning the flood intensity is shown, e.g. the distribution of flow velocity. Examples for flood hazard maps are:

Table 2. Proposal for systematic flood mapping at the local scale

Type of map	Definition
Flood danger map	Shows the spatial distribution of the flood danger without information about the exceedance probability
Flood hazard map	Shows the spatial distribution of the flood hazard, i.e. information on flood intensity and probability of occurrence for single or several flood scenarios
Flood vulnerability map	Shows the spatial distribution of the flood vulnerability, i.e. information about the exposure and/or the susceptibility of flood-prone elements (population, built environment, natural environment)
Flood damage risk map	Shows the spatial distribution of the flood damage risk, i.e. the expected damage for single or several events with a certain exceedance probability

- map of the inundation area for the 100-year flood, showing the distribution of the water depth within the flooded area,
- map of inundation areas for events with different return periods, e.g. overlaying the flood limits of the 10-, 20-, 50-, 100-, 200- and 1000-year event (see Figure 3).

Flood hazard maps contain a statement about the exceedance probability. Maps without this information are termed *flood danger maps*. These maps show historic or synthetic flood events. Examples are:

- map of the inundation area for a historic flood,
- map with the distribution of the water depth (or another parameter like the duration of flooding, the thickness of mud or sedimentation layer) for an observed flood,
- map of the expected flooded area for an extreme scenario, e.g. the Probable Maximum Flood or for the breach of a river levee,
- map with locations, where specific threats may be expected in case of a flood, e.g. areas of high flow velocity, potential locations for blockage of bridges due to driftwood, areas of potential severe erosion.

3.2. Flood Vulnerability Mapping

To illustrate the consequences of floods on society, the built environment and the natural environment, flood danger maps or hazard maps have to be combined with

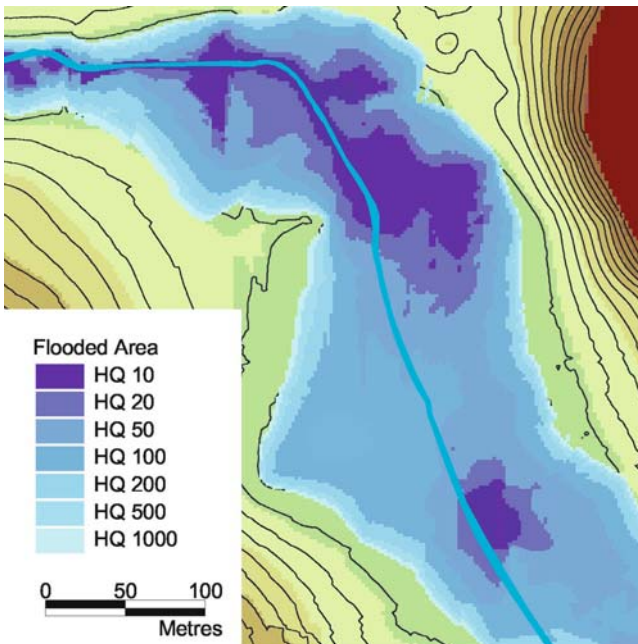


Figure 3. Flood hazard map: 10-, 20-, 50-, 100-, 200-, 500-, 1000-year inundation areas

information about vulnerability. Since vulnerability is composed of two aspects, exposure (or damage potential) and susceptibility, there are different types of vulnerability maps. Firstly, there are vulnerability maps that inform about the flood exposure, e.g.:

- map of a historic flood and the flooded buildings and infrastructure facilities,
- map of the 1000-year inundation area and the buildings which would be flooded (Figure 4),
- map of an area in the hinterland of a river levee with the distribution of the time after which different land parcels would be inundated in case of a levee breach,
- map of a worst-case flood scenario and the damage potential showing the assets that are flood-prone.

Secondly, vulnerability maps may illustrate the susceptibility of elements at risk, e.g.:

- map of an area in the hinterland of a river levee with the expected degree of damage (low, medium, high) of the buildings that would be flooded in case of a levee breach,
- map of particularly susceptible elements within the 100-year inundation area, that need special consideration in case of floods, e.g. kindergartens, hospitals, nursing homes etc.

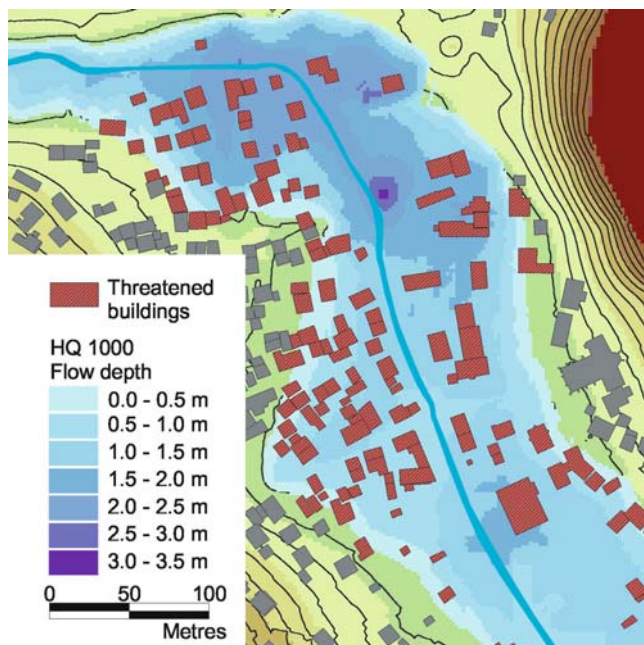


Figure 4. Flood vulnerability map: Distribution of water depth for the 1000-year flood and affected buildings

3.3. Flood Risk Mapping

Following the definition of risk in section 2, flood damage risk maps show the spatial distribution of the damage risk. Usually, they are based on a number of synthetic events with different exceedance probability. Examples are:

- map with the distribution of the flooded land parcels for the 1000-year flood including statements about the expected monetary damage,
- map of the flood-prone areas including statements about the expectation of monetary damage.

Figure 5 shows a flood damage risk map, containing the 1000-year flood and the expected direct damage in €/m². In this map the damage risk is related to the areas of the land-use plan. To this end, the expected damage of all buildings within the parcels with the same land use was summed up and divided by the sum of the building area of these parcels. In this way, the map shows the mean damage that is expected for a certain land use (e.g. private dwelling) for the 1000-year flood.

Figure 5 shows only a part of the total flood risk. A widespread indicator of the risk is given by the damage expectation (equation 11), that is the mean annual flood damage. Figure 6 shows the annual damage expectation in €/m² related to the areas of the land-use plan. The damage risk is expressed in five classes, from very low to very high. Areas with large assets that are frequently flooded have the

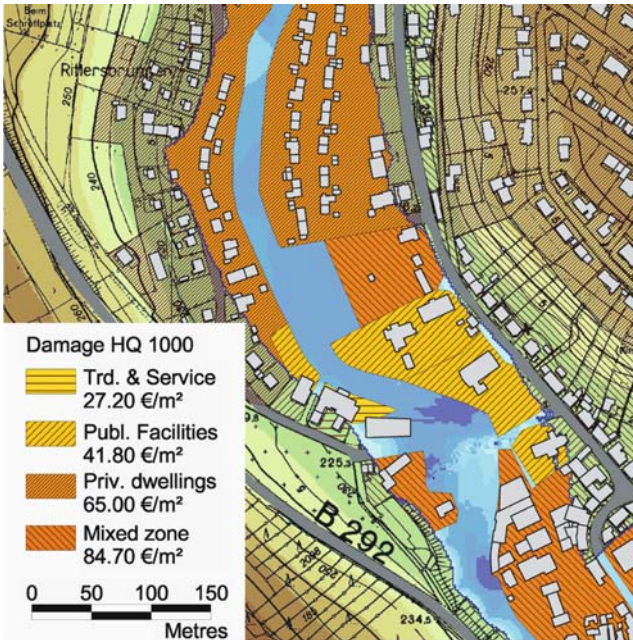


Figure 5. Flood damage risk map: Distribution of the damage in €/m² to be expected for the 1000-year flood. The damage is related to the areas of the land-use plan

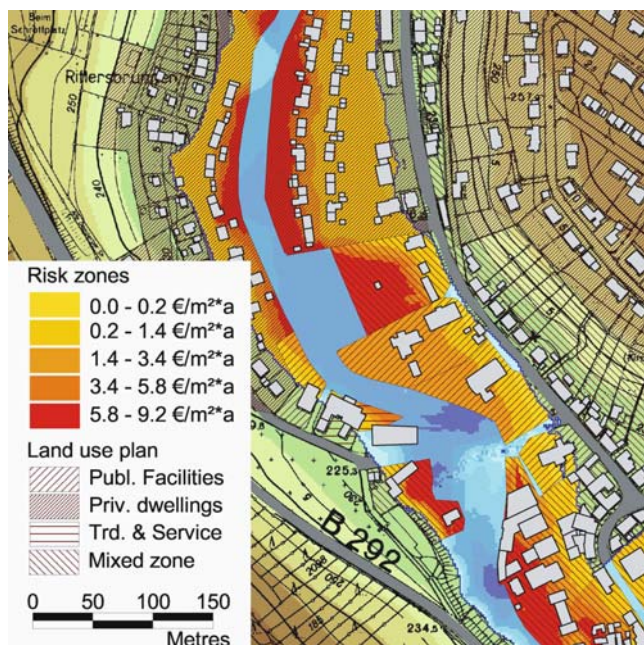


Figure 6. Flood damage risk map: Distribution of risk zones, expressed by the expected annual damage related to the areas of the land-use plan

highest risk. The damage risk is not constant within a certain land-use zone since the hazard varies within the land-use zones.

4. DISCUSSION

The described types of flood maps require different data, expertise and effort, and they may differ in their reliability and their usefulness for end-users. The following sections discuss the necessary effort, the need for updating, the reliability and the usefulness for different end-users of the various map types.

4.1. Efforts for Developing and Updating Flood Maps

There are different methods to quantify flood hazard, vulnerability and risk. Accordingly, the effort for developing flood maps may vary dramatically. This will be briefly discussed for the estimation of the flood hazard. Flood hazard estimation requires at least the calculation of an inundation scenario and its associated exceedance probability. Maybe the most widespread and simplest method is the use of flood frequency analysis coupled with a simple hydraulic transformation. Based on observed discharge time series a flood frequency curve is derived and

extrapolated to the required return periods. With the help of the rating curve (stage-discharge function) the discharge values are transformed into water levels. To obtain the inundation areas, the water levels are overlaid with a digital elevation model assuming the horizontal water surface to be perpendicular to the flow direction. This approach builds on several assumptions and may yield unsatisfactory results, e.g. if:

- the required return periods are clearly outside the observed range, and the extrapolated discharge values may not be reached due to retention effects in the river reaches upstream, e.g. overtopping of levees for large discharges,
- the rating curve is only valid for low to moderately high discharges, as it is mostly the case,
- high flow velocities and strong dynamic effects may be expected which may corrupt the assumption of horizontal water surface perpendicular to the flow velocity,
- hydraulic controls in the floodplain, such as embankments and elevated roads, are not correctly represented in the digital elevation model.

More sophisticated methods use rainfall-runoff models for the processes in the catchment and 1- or 2-dimensional hydrodynamic models for the processes in the river and floodplains (Todini, 1999, Wernert, 2001). However, such computations may become very complex, data-demanding and costly.

Generally, the amount of information that is necessary for the development of flood maps increases from a flood danger map to a flood damage risk map. The least costly maps are danger maps that show the flooded area for an observed event. Such a map only requires the observation of the inundation area, e.g. via aerial photos or via interpolation of water level markers. A flood damage risk map requires hydrological and hydraulic calculations for the estimation of the flood hazard which has to be linked to information about the exposure and susceptibility. This may require the estimation of a number of flood scenarios with different return periods, including events with large return periods.

Flood damage risk mapping may be particularly costly. The quantification of vulnerability requires data which are often not available with the needed reliability. Additional data may be necessary, e.g. extensive surveys to provide detailed information about the damage potential of the flood-prone area and flood damage functions. For very important objects such as large buildings or installations with high damage potential it may even be necessary to derive vulnerability estimates through personal interviews with property owners, plant managers etc.

Although in general, the effort increases from flood danger maps to flood damage risk maps, there are exceptions to this rule. This is the case, if a flood danger map is required to contain information about the distribution of flow velocity and flow depth which has to be provided by 2-dimensional hydrodynamic modelling. Contrary, it is possible to provide damage risk maps with much smaller effort, e.g. by using very simple approaches for the hydrological and hydraulic processes and for the damage estimation.

Flood maps have to be updated in order to take into account developments that significantly affect the flood situation. The required time interval for updating depends on the rate of change of these developments, such as changes in the retention capacity of the catchment, changes in the exposure (e.g. urban development) or climate change. Unless there are large civil engineering works, e.g. construction of flood retention basins, the rate of change in flood hazard can be expected to be small. The rate of change in vulnerability, e.g. due to decreasing flood risk awareness or accumulation of assets in flood-prone areas, is expected to be larger. Flood damage risk maps are based on both, hazard and vulnerability, and have therefore the lowest life time. Besides the rate of change in hazard and vulnerability, the purpose of the flood maps should be taken into account. For flood-prone areas with high damage potential, e.g. urban areas with large density of people, industrial areas with expensive machinery or the possibility of release of dangerous pollutants, an updating interval of a few years seems necessary.

Burby (2001) discusses the updating problem for the U.S. National Flood Insurance Program. It is required that every community is screened at least once every five years to determine the need for map revision. According to the Association of Floodplain Managers (2000), “thousands of stream miles require restudy”.

4.2. Reliability

Flood maps are provided for events which are outside everyday life experience. They mainly show situations which have not been observed before. Consequently, validation of flood maps is usually difficult and such maps are expected to be uncertain. Potential sources for uncertainties are:

- data quality, e.g. DEM resolution and accuracy, gauge data, information about assets,
- data processing algorithms and methodological approaches, e.g. derivation of inundation areas by water surface interpolation,
- extrapolation to rare events without enough data for validation of model results.

There are some aspects which are particularly uncertain. This relates to the estimation of extreme discharges and water levels. In many cases, scenarios with return periods of more than 100 years are estimated on the basis of flood frequency analysis and rather short time series. In addition, flood frequency analysis builds on the assumptions of stationarity and homogeneity – assumptions which are increasingly questionable due to changes in the catchments or climate conditions (Klemés, 1993, Jain & Lal, 2002, Milly et al., 2002).

Another big source of uncertainty is the vulnerability of elements at risk. Flood damage modelling is a field which has not received much attention and the theoretical and empirical foundations of damage models are weak (Wind et al., 1999, Merz et al., 2004). In most cases, the uncertainty of the vulnerability estimation can be expected to be high, so that object-specific statements, e.g. related to single land parcels, infrastructure elements or buildings, can not be made with sufficient

reliability. Detailed maps showing the risk of single objects implicitly carry a fictitious accuracy. For this reason, the risk statements in Figure 5 and 6 have not been related to single objects but have been aggregated to areas of the land-use plan.

The quality of flood maps should always be carefully validated. This could be accomplished by checking the results against historic inundation events and reported flood damages. For many flood scenarios such validation data will not be available. Therefore, the techniques and the data used to prepare the map should be specified. The quality and reliability of maps depend very much on the quality, resolution and completeness of the data and the suitability of the techniques used to derive the maps. The expected range of errors should be documented and it should be ensured that the methods are so explicit that the user can assess their suitability. Results should be documented in such a way that everyone using them is bound to be aware of their limitations (Clark, 1998). Given the limited possibilities for validation and the manifold sources of uncertainties, flood maps should be prepared using consistent, scientifically-based and reproducible methods.

More than previously, it is necessary to raise users' awareness of the limitations of flood maps. Users tend to perceive flood maps as accurate, even for such uncertain things as the 500-year flood damage scenario. Flood maps should, as far as possible, indicate the error range and provide the user with a realistic idea of their accuracy.

4.3. Use of Flood Maps

Flood mapping is a necessary step for developing flood risk management strategies. Flood maps can serve several purposes, e.g.:

- raising awareness among people at risk and decision makers,
- providing information for land-use planning and urban development, investment planning and priority setting,
- helping to assess the feasibility of structural and non-structural flood control measures,
- serving as base for deriving flood insurance premiums,
- allowing disaster managers to prepare for emergency situations.

In some countries, flood mapping is directly linked to land-use regulations, buildings codes and insurance. For example, in the United States flood insurance is connected to flood mapping. Communities must meet Federal Emergency Management Agency (FEMA)-approved flood mapping requirements to be eligible for flood insurance. FEMA's Federal Insurance Administration runs the National Flood Insurance Program (NFIP) which makes flood insurance available to residents of communities that adopt floodplain ordinances. More than 18,000 communities participate and more than 3 million home and business policies are in force. Insurance rates are based on classification into rough zones. These include zone A for property located within the 100-year flooded area, and B and C for property with a smaller degree of flood hazard (Burby, 2001).

As consequence of the severe flood damages in August 2002, the German Parliament adopted in July 2004 the 'Flood Control Act'. This law requires the

country-wide mapping of 'inundation zones', defined as the 100-year flood area, and the mapping of 'flood-prone zones', defined as the area that would be inundated by the 100-year event if flood protection would fail. It does not only introduce a nation-wide standard for defining flood hazard, it also relates these zones to land-use regulations. Communities are now required to note statutory inundation zones and flood-prone zones in their binding development plans (Petrov et al., 2004).

Grothmann & Reusswig (2004) have shown that the willingness of people in flood-prone areas to take their share in damage mitigation depends, among others, on the efficacy and costs of self-protective behaviour, and on the perceived ability to perform these actions. Efficient public risk communication aiming at motivating residents to take precautionary actions should not only communicate the threat of flooding and its potential consequences but also the possibilities, effectiveness and costs of private precautionary measures. Therefore, flood maps should not only illustrate the hazard (inundation areas, water depths etc.) and possible consequences (interrupted traffic lines etc.) but also information that could be helpful in case of a flood. Such information could be evacuation routes, disaster management centres, hospitals, fire brigades etc.

Flood maps give a more direct and stronger impression of the spatial distribution of the flood risk than other forms of presentation (verbal description, diagrams). Good maps allow to clearly communicate with end-users. Wrong use of cartographic techniques can lead to wrong interpretations and misunderstandings (Bartels & van Beurden, 1998). Therefore, it is important to consider the message to be conveyed and the users to be reached. For example, quantitative risk statements may be presented by means of categories (zones from low to high risk). Different classbreaks can lead to different interpretations and different spatial patterns of risk (Bartels & Beurden, 1998).

5. CHALLENGES

5.1. Vulnerability and Risk Mapping

Maps should inform about the possible consequences of floods. Ideally, this should include all types of consequences on population and society, on the built environment and the natural environment. In most cases flood maps are limited to hazard aspects. Vulnerability aspects are only considered insofar, as the land use information, e.g. cadastral data, is overlaid with the hazard information. More specific vulnerability and risk information, e.g. information about the susceptibility of different elements at risk or the distribution of potential sources of contamination (e.g. enterprises processing substances hazardous to water), are the exception.

This lack is related to the low state of knowledge in flood vulnerability analysis. The estimation of flood consequences is still in its infancy. Existing approaches focus on direct economic damages, other damage types, e.g. adverse consequences on population or indirect economic losses, are largely neglected. There is a strong need for more comprehensive studies on flood vulnerability.

5.2. Dynamic Flood Mapping

Flood maps are often perceived as static. But actually, the scenarios or situations shown on maps are conditional on certain events or assumptions. For example, seasonal effects may lead to significant differences between the flood risk in summer and winter. Another example are small-scale temporal changes in vulnerability. The damage risk of a river reach with camping sites in the flood plains may vary dramatically between the camping season and the rest of the year. For different flood map users, e.g. disaster managers, it would be valuable to have flood maps that include this dynamic behaviour. For them, a flood map showing a typical or average situation, may not be very helpful.

5.3. End-User Involvement

Recently there has been a shift of paradigms of risk-based decision making. Recent paradigms call for a participatory process in which the different stakeholders are involved early in the assessment procedure (Amendola, 2001). On the one hand, the knowledge of the research community has to be communicated to users and the uptake by end-users has to be facilitated. On the other hand, the expertise, the perspectives and values of the stakeholders need to be taken into account. Following this change, the potential users of flood maps, e.g. land-use planners, emergency managers, the public, infrastructure owners, should be involved in the process of flood mapping.

With the aim of contributing to a broader understanding and responsibility the Asian Disaster Reduction Center advocates a community-based flood hazard mapping approach (ISDR, 2003). The idea of this approach is that the community itself develops maps which show possible flooded areas, evacuation routes, disaster related facilities etc. In this way, the members of the community develop a better understanding of their risk and discuss possible disasters and mitigation measures.

5.4. Cross-Border Flood Mapping

There are no harmonised European concepts or standards for flood mapping. Even within the same country, e.g. in Germany, different concepts are used. Decision makers, governments and the public are confronted with a variety of approaches to flood mapping. Harmonised concepts would allow to (a) compare the flood risk between regions and countries, (b) give the “big picture” concerning flood risk on a larger scale, and (c) would facilitate the communication between map users of different regions.

Harmonised concepts are of particular importance considering the difficulties of validating flood maps. Since validation is only partially possible, harmonized concepts would give more confidence in the results; also for areas where no sufficient calibration is possible.

5.5. Real-Time Flood Mapping

New technologies such as satellite- and airborne-based remote sensing and developments in the information and communication sector will decrease the efforts and costs for mapping, and will increase the quality of flood maps. This allows the development of real-time flood mapping. Maps can be produced during a flood event, e.g. showing in real-time the effects of disaster management activities. Jones et al., (2002) developed a system, consisting of hydrodynamic modelling, geographic information system processing, and internet map serving, supported by new data and application automation, for near-real-time simulation of flood maps. The system automatically retrieves weather forecasts and prepares input to the hydraulic model. The results are transferred automatically into flood maps in formats suitable for an internet map server. In this way, users can select the information they want, e.g. select map layers, scales, via the internet. Such developments provide a significant benefit to the flood-affected population and disaster management compared to the forecasts of discharges and water levels which are the rule today.

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CHAPTER 14

FLOOD MODELLING AND THE AUGUST 2002 FLOOD IN THE CZECH REPUBLIC

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Abstract: In August 2002, disastrous flood came to the Bohemia in the Czech republic and heavily hit all main rivers and cities located on those rivers. Return period of August 2002 flood exceeded 800 year in some cases and the flood itself was the highest observed flood ever in most of the cities. This flood touched also Czech biggest and capital city Prague. Thanks to the hydroinformatics tools applied during flood situation, valuable information and knowledge regarding flood propagation and flood extend was available in advance. The chapter is dealing with applications of detailed mathematical models focused on determination of flow characteristics (water levels, water depths and velocity distribution) during statistically generated floods as well as real flood events. These results are used in the next step for delimitation of flood zones and allow an analysis of necessary flood protection measures in the whole river basin. This helps to solve problems of continuing urbanisation and economic growth in the areas exposed to floods, associated with further increase of population and related danger of potential economic and cultural damages. It is necessary to designate these areas as flood plain areas or areas exposed to special floods and to regulate adequately their use. This task is impossible to fulfil without strong and well-tested hydroinformatics tools as Digital Terrain Model DTM, hydrodynamic models and Geographic Information System GIS tools. The article concentrates on different approaches (1D and 2D) and different applications of mathematical models as supporting tools for decision makers on field of flood risks and flood protection in Czech republic, approved by real catastrophic flood situation

Keywords: flood protection, flood measures, flood plain, Vltava river, hydroinformatics, flood modelling, mathematical models-1D and 2D, rainfall-runoff models

1. INTRODUCTION – THE GENERAL SITUATION

For the Czech Republic, floods represent the highest direct risk stemming from natural disasters, and they can be a casual factor of serious crises, which can be associated with high material property damages, ecological and cultural damages

and also losses of human lives. The above facts were fully proved during catastrophic floods that occurred in summer 1997 and 1998, but primarily in 2002.

At the beginning of nineties, systematic preventive measures were not appropriate, because the last floods with fatal consequences occurred in the Czech territory at the end of 19th century. For example, in Prague, there have not been observed any severe floods since the 1890 (Q_{100} flood) until the damaging flood in August 2002 (See Figure 1). An absence of any systematic concept in flood protection and lack of executed flood protection measures were unfortunately notorious for the period of last four decades of the last century. Market-driven economy also did not recognise a priority in flood protection in late nineties, so it was possible to recognise a rather low level of awareness of the flood risks and certain stagnation of activities focused on the development of preventive flood measures systems in last decades. In 1997, when severe flood stroke the large areas of the Morava River basin, things changed. Based on the detailed result assessment of this catastrophic flood and experience gained from rehabilitation activities, the Czech Government has assigned a task to prepare a Flood Protection Strategy as a basis for systematic approach in this area and a basic document for preparation of necessary measures. The Flood Protection Strategy has been issued as a document integrating basic technical knowledge and skills in the region of Central and Eastern Europe with flood management, experiences from previous floods and taking into account technical standards, legislation and organisational framework in formulating further actions to achieve reduction of devastating flood impacts. Another objective was to form a basis for the state or local administration in making decisions concerning the selection of specific flood measures and to influence regional development.

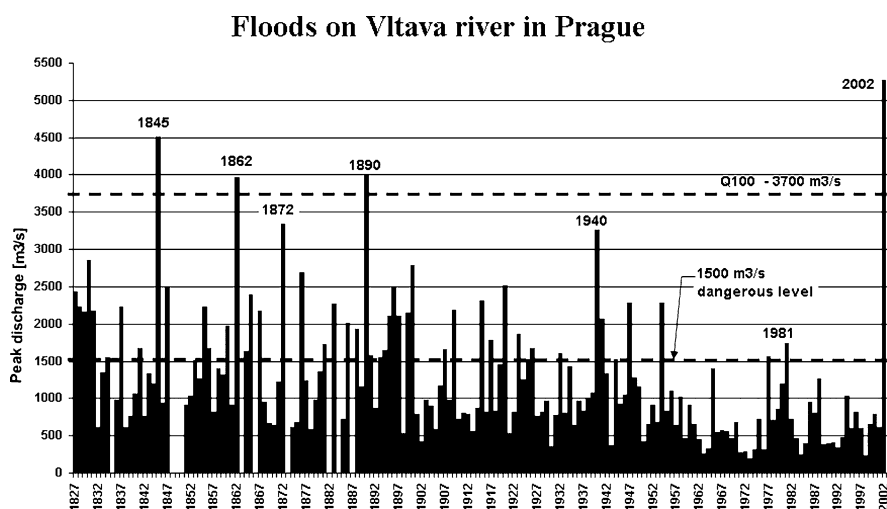


Figure 1. A comparison of floods occurred in Prague within last 175 years—source Chmí, 2002

The Flood Protection Strategy helped to speed up many flood protection measures and improved non-structural measures and flood rescue plans. Unfortunately, only a few of the planned flood measures were executed and finished before August 2002.

Since the mid nineties, the mathematical modelling has commenced to be used as a tool for gaining important information, essential for the flood protection planning. On the example of the Prague Flood Model development, we show how the things has been moving over the years in the Czech Republic.

2. FLOOD 8/2002 – SITUATION

Meteorological situation, which caused the flood, could be shortly described as type of rare condition, where two rather well-developed frontal borders had remained unusually long time above the Czech territory.

During the first wave of precipitation (6.8.–7.8.2002), mainly the southern Bohemia was affected by precipitation having totals in average between 130 and 220 mm during two days (it means the return period between 50 and 100 years). Retention of land in rural areas in the south-bohemian river basins (the basin of the Vltava River) was exhausted during the first wave, causing the increase of the discharge to values between Q_{20} and Q_{100} (it means 20 years or 100 years return period) in upper parts of the Vltava River basin.

During the second wave of precipitation (12.8.–14.8.2002), average totals were about 160 mm, in mountain areas even over 400 mm, but nearly the whole area of Bohemia and part of the southern Moravia were hit, see the Figure 2. The situation can be characterised as a combination of long-time regional precipitation of low intensity (return period about 50 years) with extremely intense local precipitation. Characteristics of the second, main wave of precipitation (long lasting, low intensity and large extent) are typical for some of previous largest summer floods in the area (1997, 1954, 1890, 1888 – see the Figure 1).

After the first wave of precipitation, the retention capacity of the upper Vltava basin was completely exhausted. The retention capacity of the reservoirs of the Vltava cascade was kept according to the valid ruling curves, but the dispatchers were helpless against the volume of water rushing down the basin. However, thanks to available limited retention volume in the Vltava cascade, the dispatchers of the Vltava River Basin Authority were able to keep the outflow of regulated cascade at the reasonable level of discharge for a while, which enabled Prague authorities to anchor all boats in the inland ports and to put up the moveable flood protection sections in the central area of Prague. This fact also assisted in the way that the other flood protection measures were in majority executed and evacuation in Prague could take place without chaotic patterns. However, due to high volumes coming from all rivers into the cascade, the outflow from the cascade became unmanageable soon, and it caused never recorded flood even in lower parts of the Vltava river reach. The situation in Prague was further complicated by the flood wave from the Berounka river, arriving simultaneously and making

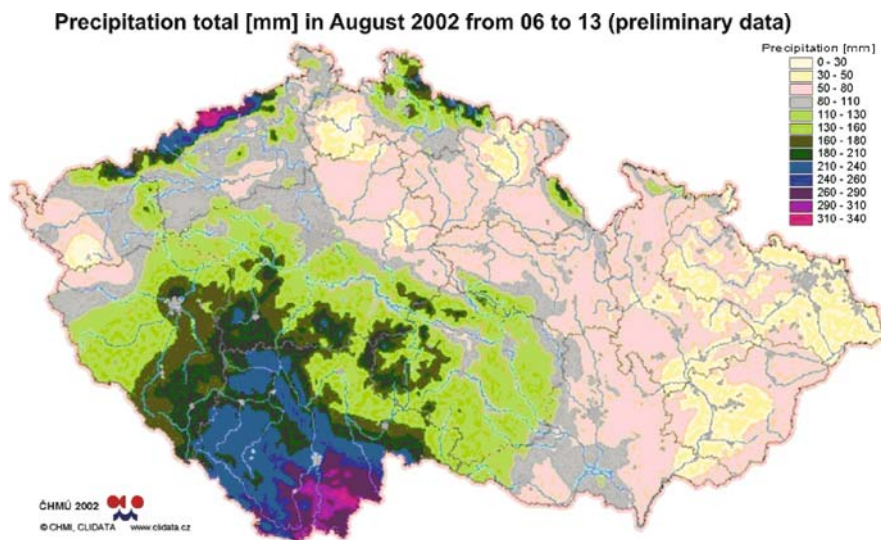


Figure 2. Precipitation total – second wave – source Preliminary report evaluating the Flood in 2002 in the Czech republic prepared and published by the Czech Hydrometeorological Institute – (29/8/2002)

the situation downstream its confluence (just upstream Prague) even worse. As the main precipitation wave covered nearly the whole territory of Bohemia, floods occurred also in the Elbe River basin, mainly on the lower reach downstream the confluence with the Vltava River. The 2002 flood was assessed as the highest recorded flood in many places (e.g. in Prague since 1827). As an example, it can be mentioned that the water level was about 0.7–3.0 m higher than that during the last comparable flood in Prague (1890). Water marks representing the peak flow were fixed in more than thousand of places in the river basins hit by the flood, and hydrologic and hydraulic evaluation of this flood begun to update basic data, formulas and models for further computation, planning and management.

Unfortunately, the hydrologic monitoring network was underinvested within the last century. During the flood, most of the gauge stations at the rivers were destroyed, some were not able to transmit or even record data under the unexpectedly high water level conditions. A meteorological forecast was available and quite accurate. Hydrological forecast was not available fully in the later stages, because most of the models were out of range and on-line data were hardly available later during the event. Rating curves were not accurate enough or do not exist for very high discharges on most of the rivers affected. All the simulations and measures until 2002 were carried out for the highest flood rated as Q_{100} . The flood 2002, rated as approximately Q_{500} , has changed the attitude of all the involved authorities.



Figure 3. The confluence of the Vltava and Berounka rivers upstream of Prague

3. PRAGUE FLOOD MODEL

3.1. The Very Beginnings

In mid of nineties, the City Council of Prague and the Vltava river Basin Authority decided to improve the preparedness of Prague against floods after enormous floods occurring in Europe in mid-nineties. During the period of preparation of the general



Figure 4. Flooded Water Research Institute T.G.M. (building on the left) and the Central Waste Water Treatment Plant (within the area laced by the line of trees)- downstream edge of Prague



Figure 5. Charles Bridge in Prague on horizon – Forefront- non-permanent flood protection barriers anchored to the pedestrian path with the reinforced foundation platform – the photo was taken during the flood 8/2002 in Prague



Figure 6. Catchment of Vltava River with major tributaries

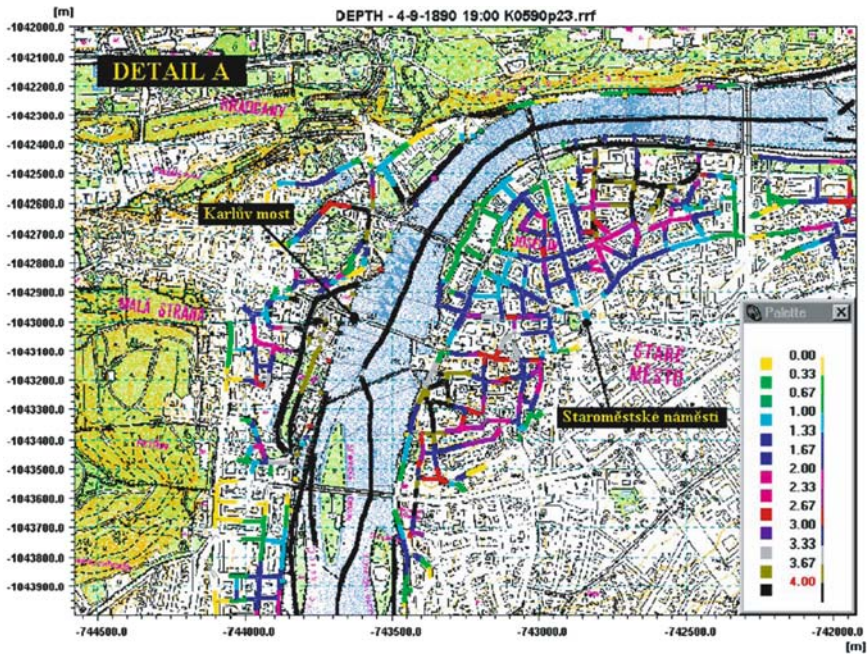


Figure 7. Simulated depth of water in the Old Town district, shown in branches-streets. The palette shows the water depth



Figure 8. Digital terrain model of the Charles bridge area



Figure 9. Velocity field close to the Charles bridge area

flood protection scheme for Prague, several alternatives were considered including ‘action 0’: doing nothing. Among the suggested solutions belonged also an initiative to build a large-scale physical model on one of the islands in Prague. This model would demand a budget of several tens of millions of Czech Crowns (approximately several hundreds of thousand €) and therefore was not accepted. After some decision-making process, the mathematical modelling tools were finally selected for an assessment of the flood protection strategy. From their results were derived measures for the Capital city Prague and its close neighbouring area. Prague is situated at the confluence of two major rivers in the central Bohemia: the Vltava and Berounka rivers, with several minor contributing streams in the area. The streams complicate the situation during the flood event, because the backwater effect could threaten some densely populated areas.

The first comprehensive study, finished in 1997, had to be based on rather complicated hydrological data set. Even though there was unique historical data available, there were also many changes in urbanised areas in the basins as well as anthropogenic changes of the river beds themselves. The study included hydrodynamic 1D+ mathematical model of Prague (looped 1D model) and also the phase of rainfall-runoff modelling. Hydrodynamic model applied the data set from the Flood event 1890, transformed for the current status of all parameters in all included basins, with the special focus on the impact of Vltava cascade. The modelling effort was among others focused on the rate of ability of the cascade to protect the city

from floods. The reality is that the volume of all the Vltava cascade reservoirs represents only the fraction of the total volume of the 1890 flood wave. This means that the cascade is able to eliminate the impact of minor floods but has only slight influence on the damaging flood events (For the flood event 1890 which is close to Q_{100} in Prague, the discharge reduction is 10% at the peak, and it can only delay the wave for several hours).

The 1890 flood event data were used after the discussion at the very beginning of the modelling, concerning the task to protect Prague at the reasonable level instead of frequently used theoretical statistically generated flood waves, and it was the first time the design flood was selected on the base of the real historical event. The peak discharge for the Q_{1890} corresponds to approximately Q_{100} (100-years return period) in Prague.

3.2. 1D Phase – The Comprehensive Study 1994–1997

The 1D hydrodynamic model covered 33-km-long river reach, limited by official borders of City Prague, upper cross section in Vrané nad Vltavou (chainage 70.000 km) and the lower one in Klecany (chainage 37.000 km).

The basic step, making any mathematical model reliable, is calibration, using the real and recorded event data. The opportunity to use a historical event for calibration was limited: The only serious flood recorded in 20th century was the 1954 flood, however, the impact of the event was to large extent influenced by empty reservoir at the dam Slapy, which was about to be completed at that time. The reservoir was empty when the flood came, and it caught the majority of the flood wave volume. Therefore, the team of modellers selected for the flood model calibration procedure flood event dated 1890 with estimated peak discharge $Q_{max} = 3.975 \text{ m}^3/\text{s}$. But, as mentioned earlier, big amount of topographical and urbanisation changes occurred in the flood plains since 1890. This had to be definitely considered. The dams cascade on the Vltava river changed the runoff pattern as if the flood went through the system of dams operated in accordance with the valid ruling curves. The rainfall-runoff characteristics are also influenced by both natural and man-made changes: building, industrial and agricultural activities. Despite all drawbacks of the event from the year of 1890, the team decided to use it for a trend-calibration, because this event was well documented not only in Prague but also on the streams in upper reaches.

The rainfall data was available for the 1890 flood event. One of the possible solutions of flood peaks prediction and storage capacity in Prague is to set a system of rainfall-runoff models in upper reaches and derive the inflow hydrographs by means of calibration of their parameters of these models.

A conceptual MIKE-NAM (rainfall-runoff) module has been applied for six sub-basins of the main Vltava river tributaries (the Sázava, Malše, Otava, Lužnice, Berounka and upper Vltava), upstream of Prague. The river Berounka is known by steep ascending legs of hydrographs which, meeting at the confluence with the Vltava river, may cause catastrophic flood events by interference. Lužnice is a river

with very slow reactions and, because most part of the basin is situated in flat low-land, provides floods with considerable volume.

The rainfall-runoff models were calibrated using selected cross-sections where hydrographs were available for a global hydrodynamic model. Because the information about rainfall distribution, intensity and space and time variability is easily available, the team decided to utilise this methodology to get more realistic dynamic boundary conditions in the form of hydrographs. The calibrated model set-up enables to simulate any boundary conditions based on known or assumed rainfall intensities at the inflow cross sections.

The details about the calibration of the second phase were presented by Zeman et al. (1996). All six sub-catchments where MIKE11-NAM was applied were successfully calibrated by comparisons with measured hydrographs from 1890. All basic simulation runs and data are available in daily time intervals. The modelling tool for generating boundary conditions is ready to be used for any future modelling activities. The global model set-up of the Vltava river basin above Prague was applied to obtain transformed flood waves based on operational rules of all large reservoirs. The operational rules were set-up by the Vltava river Water Basin Authority dispatchers, who were present during the simulation works, setting the conditions on structures according to real cases. This approach was the only one accepting the human decision influence during the rainfall-runoff process, where hydraulic structures have essential impact on hydrodynamic characteristics.

The 1D hydrodynamic model was developed in two phases: in the first phase, the river channel model was built and in the second phase, the flood plain model was connected to river channel model.

Both of them were based on open channel modelling scheme. There were 390 cross sections describing the open river channel in the 33-km-long river reach. All the important hydraulic structures from the area of interest (such as bridges, weirs, derivation channels, inland ports, islands and locks) were introduced. All the topographical information was derived from the technical maps in scale 1:500, which were available in a sufficient quality.

The river channel set-up was completed comprising 385 cross sections, 5 weirs (Modřanský km – 62.22, Šítkovský km – 54.32, Staroměstský km – 53.93, Helmovský km – 51.15 and Trojský km – 45.67), 5 navigation locks (Modřany, Smíchov, Štvanice, Trója, Podbaba) 16 bridges, 7 islands and 4 inland ports.

In the second phase, the flood plain model set-up was derived from the river channel set-up. This model was created on the same river reach as the river channel set-up but has to cover all of the effective flood areas flooded by extraordinary flood events. The schematisation for the flood plain model set-up was based on MIKE11 1D+ modelling facilities (looped schematisation). This means that the flood plain was divided into particular looped channels, described by cross sections and covering the responding part of the plain. This was the first real case application of the looped system in the region. The model set-up had to allow the user to model all the most important flood stream flows and storage capacity to describe transformation of any flood event hydrograph without significant phase and amplitude

error. The methodology adopted by the team seemed to be rather complicated, but in mid-nineties it was the only method that enabled the Vltava Water Basin Authority representatives evaluate all future design ideas of flood protection measures of Prague. Few parts of the area of interest were studied using 2D models, because the schematisation made in 1D+ would be too inappropriate and coarse, but the level of hardware did not solve more than selected details of the flood plains using the 2D methodology.

The first sub-reach of the flood plain model set-up was completed at the end of 1995, the rest of the model was completed during the 1996. The most complicated parts were sub-reaches covering Malá Strana and Staré Město – two most valuable historical city parts in the flood area.

The critical area of Staré Město (old town – the historical centre of Prague), at the cross section of the Charles Bridge, was the subject of examination using the 2D methodology.

Although the Charles Bridge belongs to the national treasure collection as a gothic master piece of architecture, it is the most significant obstacle for free flow through the open river channel of the Vltava in Prague domain. Moreover, the bridge serves usually as trap for all kind of debris and floating logs. The objective was to provide a set of recommendations and technical measures increasing the safety in case of the flood event.

FLUVIUS simulation tool was used, based on numerical integration of the complete non-linear equations for 2D unsteady flow in the horizontal plane. This tool was able to handle flooding and drying of the flood plain and various methods for bed resistance calculation were used in the package.

The results, outputs and model set-ups were supposed to be used for several purposes:

- flood mapping for city layout plans
- rescue operation planing for emergency situation when Prague is flooded (velocities, depths and discharges in particular places of interest)
- evaluation of new flood mitigation plans and their impacts on overall flooding conditions and flood wave propagation in the given territory
- evaluation of operational rules of the Vltava River Basin Authority under the flooding conditions
- preparation of mapping outputs for GIS layers supervised by the city council of Prague and similar data processing activity for the Vltava River Basin Authority GIS
- support for detail city planning activities

All these aspects were utilised by the city council authorities. The flood mapping results were accepted. Comprehensive comparisons with the former flood contours were done and areas, where former and modelled flood lines differed, were found. The largest area was for example the part of the old town known as Na Františku, which had been indicated in former maps as a dry area, and the study discovered that the area will be probably flooded by backwater effect.

The project was planned for the period of 38 months. The results obtained were considered to be consistent with the goal and objectives. Project results provided the values as maximum water levels, flooded areas extent and volumes in more general view than ever before. The responsible authorities used the 'calibrated' model for answering questions related to the investments for flood protection measures. The plans for development in the city centre and suburbs were corrected according to model results. The weakest points of flood defence were specified, and suggestions for improvements were assessed. The results of the flood protection master plan represent the most important application of hydroinformatics tools in the Czech Republic in that period.

As already mentioned, at time when the comprehensive study was carried out, the available computer technology was not able to provide a support for 2D modelling effort at large areas. The 1D approach could be in many cases accurate enough to give answers for some questions. The 1D models are still successfully used in certain types of flood plain areas, and fast computation is still their most advantage. The 2002 flood proved that most of the conclusions based on this study were correct and in some cases provided the crucial point for decision-making process of the local authorities – the best example are the mobile barriers that finally saved the city centre – old town – in August 2002.

3.3. 2D Flood Model 2000–2001

After the successful application of the first 1D Prague Flood Model, the cooperation with the Vltava River Basin Authority and the City council authorities continued. Newly developed tool for 2D modelling – MIKE 21 C– was used to update the Prague Flood Model.

The MIKE 21C package was specifically developed for modelling of river morphology. It uses a curvilinear orthogonal grid, which enables to build the mesh, suitable for description of the real morphology to decrease number of computational grid points. Using of 2D approach updates and enlarges information about the water flow in the city under the flooding conditions. Maps of flow directions and velocity are obtained over flooded area, as well as complete water surface elevations pattern. But the essential reason, why to use the 2D model, is the better accuracy in those parts of the flood plain, where it is not possible to predict exact flow direction – reaches, where flow is supposed to leave the centreline of the main channel (or side channels) and flows through wide inundation areas. With such flood plain conditions, it is extremely work demanding and often impossible to build the 1D model, which would give valid results. There are several such areas across the Prague Flood Model. Two of them, Holešovice-Karlín and Trója, were schematised as separate models to test MIKE 21C modelling package and to obtain some extra information about the flood conditions in these areas. The results revealed some interesting moments, which could not be recognised in the original 1D model – the flow directions were often rather different from the original estimation, which had the significant influence on overall stream behaviour in these areas. These two

mentioned models were later merged, creating the downstream one of three parts of 2D Prague Flood Model 2000. The network sustained from 1,081,348 computational nodes and consisted of three parts: the lower part Roztoky –Karlín (326,402 nodes), followed by the middle part Centrum (397,736 nodes) covering the central part of the city and the upstream part called Soutok (357,210 nodes), including the Vltava and Berounka Rivers confluence. The spatial resolution of a grid varied between 2–3 metres, necessary for describing the Staré město – old town area with narrow and winding streets, and 5–9 metres in the floodplains, less important areas. Division of the whole 31-km-long river reach of Prague area was necessary, because the computations appeared to be extremely time-demanding. Also because 1D model was already built, it was decided not to use fully dynamic simulations through the whole flood wave time period, as it had been done in the case of 1D model, but to carry out steady state simulations, using the peak discharge of modified 1890 wave, result of the rainfall-runoff simulations from the 1997 Comprehensive Study. Main interest was focused on peak discharge of the event at that time.

The example of the results is shown in Figure 10 and Figure 11. The 2D modelling technology rapidly increased the usability of models, because the combination of flood depth maps and velocity fields allowed to assess endangered zones during the floods, and these results are very valuable for preparation of flood management plans and evacuation planning maps.

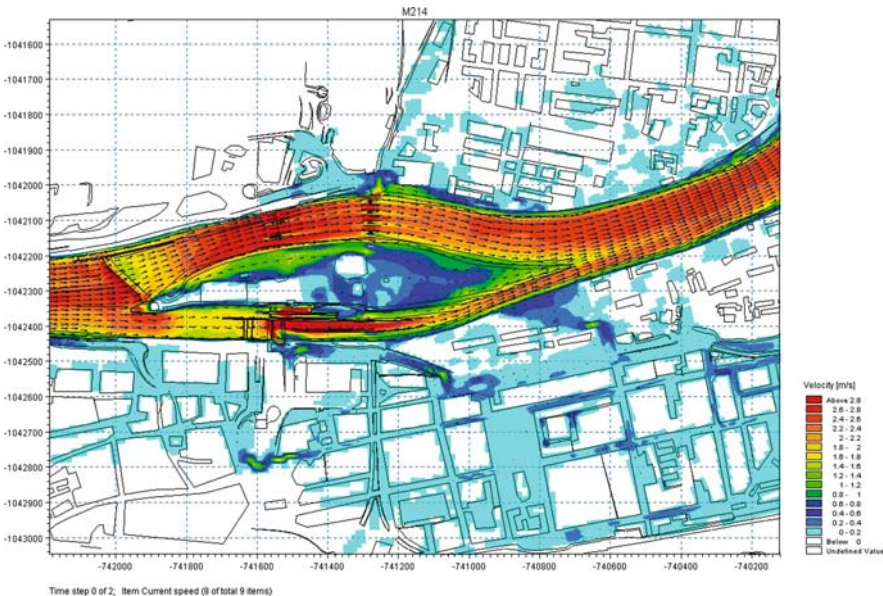


Figure 10. An example of the velocity field – flood mapping in Prague

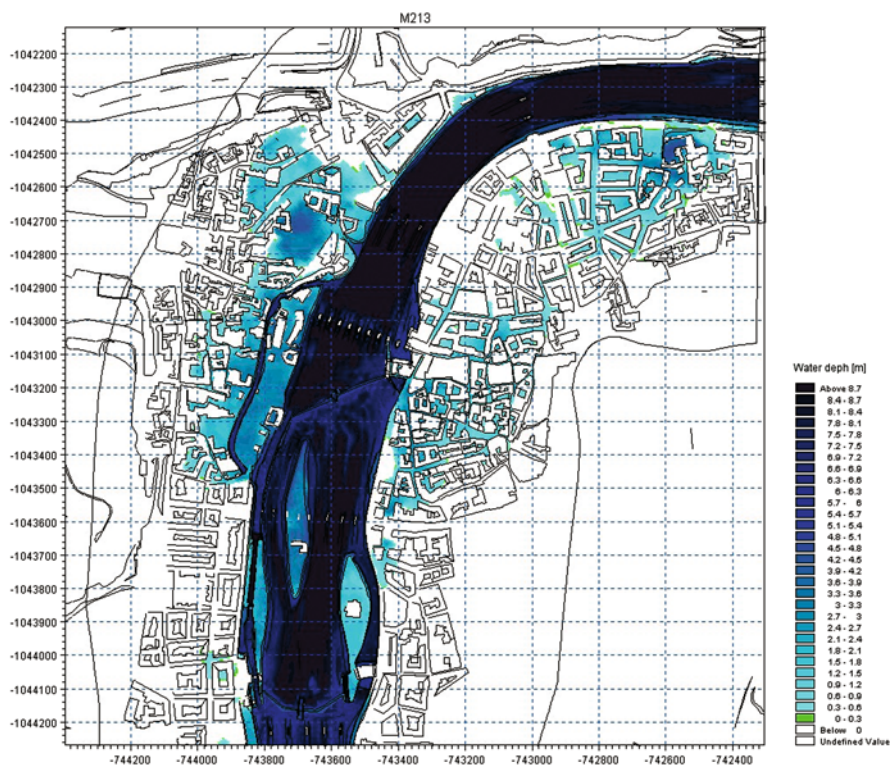


Figure 11. An example of the water depths in Prague generated by M21C model

Parts of 2D model were used for assessment of various projects in the flood area, and for the first time it was also used for validation of a design of particular flood measures.

As a disadvantage of 2D approach could be stated fact that the computational time for dynamic simulations was enormous. Nevertheless, the benefit of the 2D approach was undoubtable, and it was obvious that it is only a question of time, when the hardware development enables the fully dynamic simulations to be performed without time constraints.

Emergency management used all the generated maps during the Flood 2002 event. Moreover, mathematical models presented here were used operatively, providing the support for the work of the Flood protection council of Prague. According to the Czech Hydrometeorological Institute forecasts, the new flood maps were generated and delivered to the Flood management committee during the 2002 flood. Rescue forces used the flood maps with clear indications of depths, water levels and in many cases also velocity fields simulated for the discharges, which were usually lower than the catastrophic ones in August 2002. But nevertheless the maps gave them some overview so needed in such cases of crisis.

After the 2002 flood event, the flood line generated from simulation results was compared with a real one (from aerial photographs taken during August 2002 – see Figure 12). Both lines are very close – the modelling was surprisingly accurate.

3.4. 2D Prague Flood Model 2003 – Update after 8/2002 Flood Event

The flood 8/2002 was definitely considerably higher than the 1890 flood, used in the framework of all the previous flood modelling studies. According to the first estimates, the peak discharge of 2002 flood reached $5300 \text{ m}^3/\text{s}$, contrary to $4030 \text{ m}^3/\text{s}$ of the peak discharge of the design flood – modified flood wave from the year 1890. As it was impossible to carry out proper calibration of the models before 2002 because of lack of relevant water marks (and also river morphology and whole basin changes), all the calibration factors – bed resistance coefficients – were set at the upper part of their ranges for safety reasons. The first part of the flood protection measures was built with rather high safety margin, which finally saved the Staré Město – old town – from flooding. But it was really tight – only a few centimetres were left out of the original 50-cm margin.

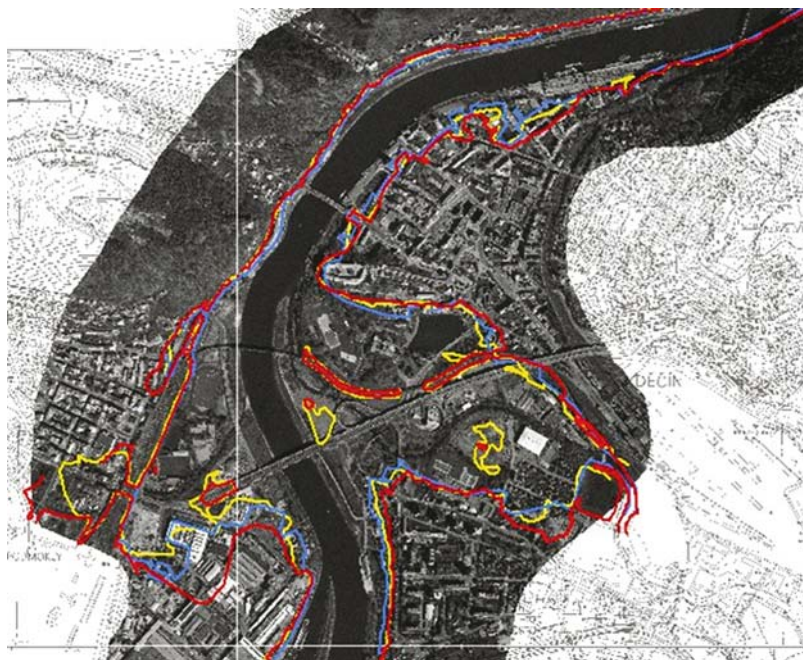


Figure 12. The comparison of real flood extent – (red line – simulated flood line for predicted discharge, blue line – the real floodline 2002/8 as maximum flooding envelope evaluated from airborne photogrammetry, yellow line – previously calculated Q_{100} flood line) – source: the Elbe River Basin Authority – 2002

After the flood was carried out re-calibration of 2D model for the peak discharge that occurred during the flood 8/2002. For this purpose, a lot of reliable flood water marks was fixed and recorded during the flood, and also the modellers were allowed to observe everything what happened in particular phases of the flood in some places.

The evaluation was very detail – a sophisticated and complex approach was required. The result was actually the general modelling study of the 2002 flood peak – steady state simulation for the peak discharge. The resulting water level is rather accurate – 69% of the reliable peak records were within the margin of 5-cm difference, and over 87% were up to 10 cm difference in comparison with computed water levels (See Figure 13).

The modelling study of the peak of 8/2002 flood was the basic part of the 2002 model. The originally planned fully dynamic simulation – the complete time run of the event could not be carried out yet because of lack of necessary boundary conditions. All the hydrographs are still being the subject of research.

3.5. Practical Application of the Re-Calibrated 2D Model

Together with the re-calibration came the further request to use the model for evaluation of the Prague Flood Protection Project design works. Prague Flood Protection Project has become really focused issue. The first basic step of the study was to assess the influence of complete designed flood protection line (actually the new border reducing the flood plain extent) on the flow conditions. In the framework

Verification at 8/2002 flood water levels – water marks

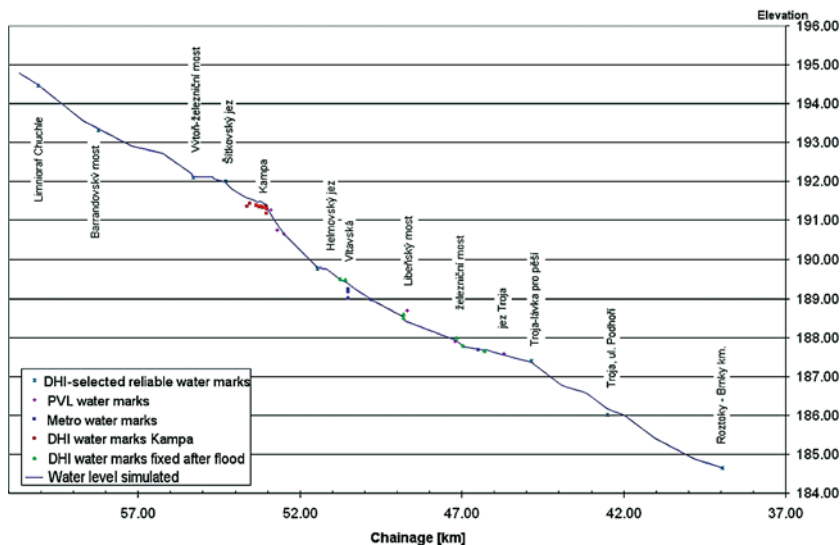


Figure 13. Verification 2002 flood water levels for peak discharge

of this task, three scenarios were assessed, varying only by their approach to flood protection of the Central Waste Water Treatment Plant (CWWTP), located on the Císařský Island downstream Prague (see Figure 14). The first scenario was the basic and assumed that the CWWTP is fully protected, the second assumed the CWWTP is completely removed and the third scenario assumed that the CWWTP would be arched over by the waterproof flat roof at the elevation of current dikes (CWWTP was designed to be protected against Q100 flood).

The last set of simulations was repeated for the 2002 flood simulation conditions taking into account existing part P0001 and proposed part P0002 of the flood protection plan (flood protection of Kampa and Malá Strana).

The first three simulations carried out to prove that the flood protection will not have negative impact on the flow conditions during the flood, successfully proved, which the Prague Flood Protection will not considerably affect the flow conditions during high discharges, because it will cut off mainly only the passive parts of the flood plains.

The impact of the CWWTP on water level changes is less than it was assumed (about 10 cm in the case of non-over topped wall), much higher effect has the cleaning of the Císařský Island and the whole flood plain area from the bushes, fences, sheds and other flow obstacles. The last simulation proved the expected fact that the Kampa protection – part P0002 almost would not affect the water level near the Charles Bridge. The discharge through the Kampa Park is only 300 of



Figure 14. Císařský Island – Central Waste Water Treatment plant (see also Figure 4 13)

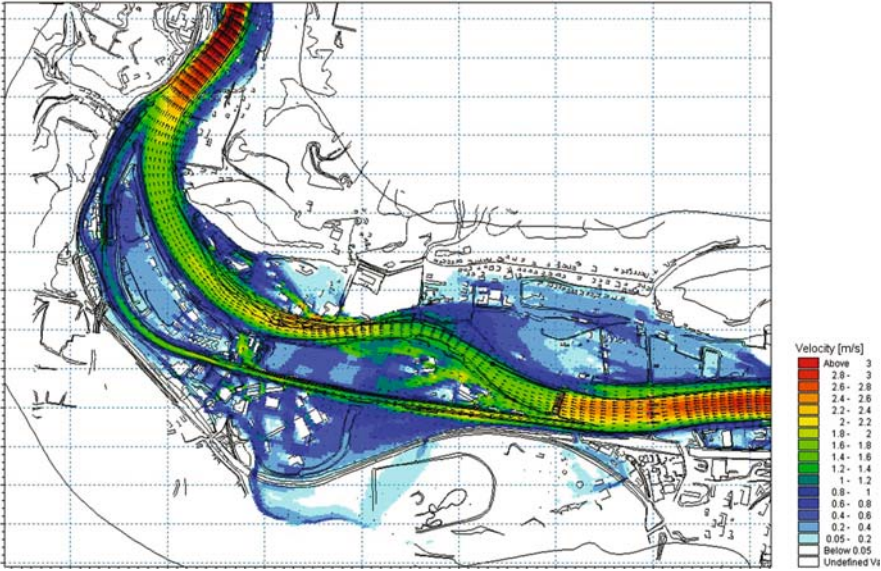


Figure 15. The example of MIKE 21C output – flow velocity in the area of Císařský Island

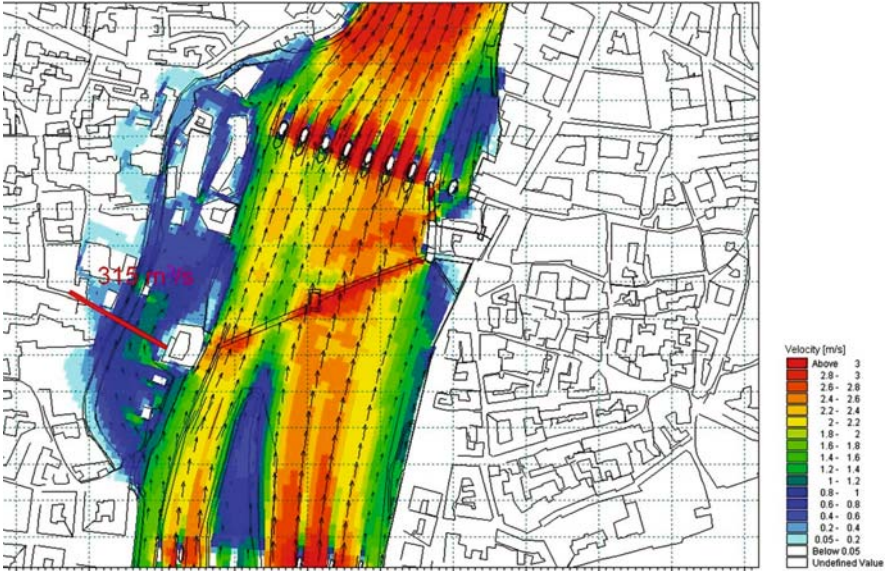


Figure 16. The detail of the Prague centre, Kampa park at the left – flow velocities and the discharge fraction

5300 m³/s the total flood peak discharge. Therefore, the conclusion was that the influence on the flow conditions is negligible (see Figure 16).

All the described results of simulations carried out were accepted by all involved authorities, and 2D Prague Flood Model has become an integral part of the design process of the Prague Flood Protection measures.

The evaluation of the final design of Prague Flood Protection will be carried out as the next task during 2004, and after the 8/2002 hydrographs evaluation, the fully dynamic simulation of the 2002 flood wave will be executed.

4. FLOOD PROTECTION – STRUCTURAL MEASURES

Most of the cities and industrial installations in the Vltava and Elbe river basins were protected in accordance with the formerly valid compulsory standards and norms for Q_{100} , Q_{50} or Q_{20} discharge. The structural measures were focused mainly on construction of reservoirs, improving of river channel capacity and primarily on designing of dikes and levees parallel to the river channels. Many of these measures resulted in cutting-off the flood plains without any previous assessment of an impact at the whole river basin. Most of the hydraulic calculations were performed on the basis of steady non-uniform flow, which in many cases means an oversimplification of the situation complexity.

A new concept was introduced by the newly defined Flood Protection Strategy (see Chapter 1 Introduction – the general situation). The most important highlights are:

- The flood management structures have to be assessed in conceptual way (the impact of the structure has to be assessed not only locally but also generally in the whole river basin), only mathematical models provide the relevant answers on impacts.
- Design floods are derived from historical floods including their dynamic characteristics. The impact of the newly designed structures has to be compared with the current situation – with and without the structure installed.
- There has to be emphasised an interest to enlarge the natural flood plain retention capacity along the river, and any restriction of flood retention volume should be compensated by other complementarily designed measures.
- Environmental aspects and hazards have to be assessed.
- Best forestry and agricultural practice has to be taken into account to increase the retention capacity in upper parts of the basin.
- Moveable (temporary) structures are very important supplementary activities in flood mitigation effort.
- A sediment transport phenomenon has been ignored in the past periods for many times, and some structures have failed to operate properly because of this phenomenon.
- Urban drainage systems (primarily sewers and local streams) have direct impact on functionality of the flood mitigation structures, and the assessment of mutual relation between two systems has to be performed to get a platform for operational

rules and actual relevance of the scheme (pumping of gravity-driven sewer system of the city with 1M inhabitants over flood water levels might create a crucial sanitation problem for longer flooding period in comparison with leakage from dikes).

- All newly proposed/designed structures have to be assessed also for the impacts of discharge considerably higher than the design flood. This is very important for flood management planning (If-then type of scenario)
- All newly designed structures have taken into account emergency scheme for the event of higher discharge (or water levels) than designed ones.

4.1. Example of Structural Mitigation Effort in Prague on the Vltava River

To provide an overview how the strategy is reflected in reality, let us take again the example of Prague Flood Protection.

Based on the results of mathematical models, there was set-up of a design water level for flood protection structural mitigation activities (with 40–60 cm high safety margin above the simulated water levels). This rule includes all designed measures (permanent and temporary structures). The concept of the flood protection in Prague uses combination of temporary and permanent structural measures to prevent flooding of the urbanised parts of Prague.

In accordance with accepted design documentation, the activity on the first phase P0001 from Masaryk Embankment to Embankment Na Frantisku was executed and completed in 2000. This phase of structural measures was designed as a temporary structure combining vertical supports and horizontal aluminium beams sealed by a rubber stripes (see Figures 12, 17).

The phase 0002 for protection of the Malá Strana (left bank) has been designed but not completed before the 2002 flood. The total investment cost of a combination of permanent and temporary constructions of the phase P0002 was calculated at the level of 240 M CZK (8 M Euro). The whole protected area of the city is further divided into six phases.

Technical parameters of the rest of planned flood protection parts will be improved based on flood 2002 experiences. The total investment in Prague will reach 875 M CZK (29 M Euro). The Prague Town Council bought 230,000 pieces of sandbags and other special equipment, which is available in case of floods (pumping capacity, special sealing beams for openings etc.).

5. NON-STRUCTURAL MEASURES

The flood protection activity contains according to the Water Act all measures, which can protect human lives and property against floods. This aim should be reached by preventive activity, increment of retention capacity of the basin area by systematic measures (e.g. new technologies for agricultural and forestry).



Figure 17. Moveable construction (see also Figure 5) as completed prior flood in 8/2002 – phase 0001 – designed by Hydroprojekt a.s. – total cost 90M CZK (3M Euro)

This definition shows that the flood protection includes the wide range of activities, not only particular structural measures.

Non-structural measures include all activities, which can help to improve the flow conditions in the flood plains. This means essentially to remove all the obstacles from the active parts of the flood plains, to clean the densely overgrown areas at the banks, islands, etc. In the case of the 2002 Prague Flood Model, the decreasing of the bed resistance in particular areas has shown the highest impact of all the studied measures. Especially in the areas, constituting certain ‘bottleneck’ at the river reach, was found considerable effect of vegetation on banks or islands, which (having high resistance against water flow) prevent faster outflow and then increase water level and flooded area extent upstream. The influence of the bed resistance increases with higher flux velocity, so the ‘bottlenecks’, where the flux velocity is high, are very sensitive for bed resistance changes. In parts, where the whole valley is narrow and closed, high bed resistance of the banks can cause water level increase even in range of metres. In all above mentioned cases, the 2D mathematical model is extremely useful tool, because it can locate the critical cross-sections on the river reach quickly and show how much we are able to decrease the water level in particular reaches.

6. CONCLUSIONS

Flood events, which hit Czech Republic in 1997 and 2002 were different, as well as their consequences. In 2002, considerably larger area of Czech Republic was hit, and the extremity of peak discharges was higher. Fortunately, it was clear that

during 2002 flood event, some of measures introduced after 1997 experience helped to save lives and property namely in capital of Czech Republic, Prague. Authorities did several very important steps in a proper direction, new laws were accepted and introduced into the daily life (Water Act, Law of Crises management and Law of Integral Rescue System), and an improvement in logistics and organisation of rescue operation during the flood 8/2002 was proved. Communication was definitely better, and co-operation among Rescue forces – Fire-brigades, Police and the Czech Army – was considered at higher level than in 1997. Water management information service (such as flood mapping) was utilised for evacuation of about 220,000 inhabitants, life lost were reported very low during the floods. It is expected that enormous loses on property were saved thanks to newly constructed structural measures of flood protection in Prague which were used during the 8/2002 flood.

Finally, the 2002 flood fully proved the usefulness of mathematical models for flood protection at any stage, for the flood measures design process, for improving the flood passage forecasting, for producing easily understood maps and charts enhancing the rescue activities. Mathematical models now have become an integral part of Flood Protection scheme in the Czech Republic.

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CHAPTER 15

SEASONAL RAINFALL AND FLOW TRENDS WITHIN THREE CATCHMENTS IN SOUTH-WEST ENGLAND

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Abstract: Hydrological and hydraulic design and analysis is dependant on the probabilistic, risk and uncertainty analysis of hydrological events. Hydrological variables are traditionally treated as random and stationary with certain probability distributions. If changes in rainfall and flow patterns are evident, they will have significant impact on existing infrastructure, current practice and future strategies in flood defence and water resources management. Recent floods in England have triggered debate on the impact of climate change on floods. In this study, trend analyses were carried out on seasonal rainfall depth, mean flow and peak flow, and return period of peak flows over three distinctive catchments in South West England. It found that there are general trends of increased volume of rainfall and runoff in winter and slightly changed volume (either in decrease or increase) of those in summer, which is in agreement with the current climatic model's simulation. However, the peak flows (both annual and seasonal) across three catchments appear to move in opposite directions, indicating the change of rainfall patterns or/and anthropogenic activities in the region. This could have significant impact on hydrological design of water engineering structures in the future due to the disparity between the flood volume and peak. The paper also illustrated the change of the return periods of flow in the region and discussed its serious implications in existing and future hydraulic engineering projects

Keywords: climate change, trend, seasonal, rainfall, flow, return period

1. INTRODUCTION

Floods are the most common and widespread of all natural disasters. It is the type of natural disaster that often causes considerable public concern, and recently floods have frequently appeared in the headlines of local, national and international media. The question of whether climate change has had an impact on the recent

extreme rainfall and flooding in the United Kingdom is in a big debate among the hydrological community (Robson and Reed 1999). It is known that hydrological and hydraulic design and analysis are dependant on the probabilistic, risk and uncertainty analysis of hydrological events. Hydrological variables are traditionally treated as random and stationary with some probability distribution (May 2001). If changes in rainfall and flow patterns are evident, they will have significant impact on existing infrastructure, current practice and future strategies in flood defence (Han et al., 2002, Clarke 2002, Cunderlik and Burn, 2003). This, as experienced recently in the November 2000 flooding in south-east England, would bring economic, social and environmental damages to the society. It is therefore crucial to determine as soon and as accurately as possible whether climate change has brought an increase in rainfall and floods in the UK.

Based on the simulated climate change, a number of researchers have attempted to assess its influence on land hydrological processes. In the UK, it is found that flows tend to be more seasonal with simulated climate change (Arnell and Reynard, 1996, Arnell, 1998). Under the driest scenario winter flows decrease less than summer flows whilst under the wettest scenario winter flows increase far more than summer flows. The south-east region is also found to be more susceptible to climatic change than the north of England. In addition, the different catchments with different physical characteristics are found to react differently to climatic change. It is also found that the changes in river flow are small when compared to yearly variability. However, these changes are noticeable across whole decades. Based on the HadCM2 experiments from the Hadley Centre, Reynard and Prudhomme (2001) carried out a study in which a continuous flow simulation model (CLASSIC) has been used to assess the potential impact of climate and land use changes on the flood regimes of large U.K. catchments in the Severn and the Thames catchments. It shows an increase in both frequency and magnitude of flooding events in these two rivers. The study also included a scenario whereby with a 50% increase in forest cover the absorption of water by the trees will be able to counteract the effects of climate change. Conversely, large changes in urban cover of catchments will have large impacts on flood regimes, increasing both frequency and magnitude of floods significantly beyond changes due to climate change alone. This suggests that the effect due to land usage changes could override climatic change. Therefore, an increase in frequency of flood may not be due solely to an increase in rainfall duration and magnitude, and a contribution from land usage changes should also be considered. This research focuses on the effects of climate change and land use change on flood frequency. Some researchers have pointed out that with the current technology, there is still a great degree of uncertainty in modelling the land use changes such as urbanisation and afforestation (Moore et al., 2000, Wheeler et al., 1999) and much more research is needed in this area. Similar work was also carried out by Sefton and Boorman (1997), Fowler et al (2000), Cameron et al (2000), etc. However, it is important to be aware that predictions from these climate models are always subject to considerable uncertainty because of limitations in our knowledge of how the climate system works and on the computing resources available. As a result, different climate models often give quite different predictions. For

practicing water engineers, water planners and policy makers, it is important to know if the climate change has already altered our hydrological rainfall and flow patterns.

Despite the numerous researches carried out so far in this area. Outcomes of these researches are still of uncertainty and, indeed, controversy. [Pupacko \(1993\)](#) found a slight trend of increasing and more variable winter streamflow in the northern Sierra Nevada since the mid-1960s. [Smith and Richman \(1993\)](#) found increases in mean annual streamflow in Illinois ranging from 20 to 80% during the period from 1950 to 1987. [Lettenmaier et al \(1994\)](#) detected strong increases in monthly streamflow across the United States during November through April for the period 1948 to 1988, with the largest trend magnitudes occurring in the north central region. [Changnon and Kunkel \(1995\)](#) found significant upward trends in floods in the northern Midwest during the period 1921–1985, and found a link between these trends and higher precipitation. [Lins and Slack \(1999\)](#) reported increasing trends across the US in lower magnitude streamflow quantiles but not at higher quantiles which indicates that hydrologically the conterminous U.S. is getting wetter, but less extreme. [Olsen et al \(1999\)](#) claim that large and statistically significant upward trends were found in many gauge records along the Upper Mississippi and Missouri Rivers. [Milly et al \(2002\)](#) found that the frequency of great floods increased substantially during the twentieth century. All these results challenge the traditional assumption that flood series are independent and identically distributed random variables and suggests that flood risk changes over time. However, [Douglas et al \(2000\)](#) rejected some conclusions from a few previous researchers and found no evidence of trends in flood flows but did find evidence of upward trends in low flows at the larger scale in the Midwest and at the smaller scale in the Ohio, the north central and the upper Midwest regions, using a 5% significance level. [Black and Burns \(2002\)](#) carried out re-analysis of flood records in Scotland and reported that no general trends in flood magnitude series were found. Recent work by [Mudelsee et al \(2003\)](#) found that through longer-term records of winter and summer floods in two of the largest rivers in central Europe, the Elbe and Oder rivers, for the past 80 to 150 yr, no trend was demonstrated in summer floods and the flood occurrence in winter has been in decline. They also concluded through a long record analysis that reductions in river length, construction of reservoirs and deforestation have had minor effects on flood frequency.

In fact, in contrast to the detection of trends in temperature and CO₂ concentration in the atmosphere, trends in precipitation and flow are more difficult to quantify due to their natural variability. Despite the coverage of the mass media, there are doubts and reservations about attributing recent floods in the UK to climate change. [Hiscock et al \(2001\)](#) analysed the flow records of the Rivers Bure, Nar and Wensum in eastern England with the aim of identifying long-term changes in flow behaviour relating to variations in rainfall amount, land use, land drainage intensity and water resources use. It was found that in the study area, and since 1931, there is no evidence of long-term change in rainfall amount or distribution, on either an annual or seasonal basis. The Flood Estimation Handbook ([Reed, 1999](#)) states that, “There is evidence to suggest that human activity is influencing the

world’s climate . . .”. However, it claims that effects of global warming on flooding of rivers is “much more speculative, . . .”. Its analyses did not show that climate change has affected UK flood behaviour. However, neither do they prove that it has not affected flood behaviour. The research also found significant year-to-year fluctuation in flooding. Robson (2002) found that there is no statistical evidence of a long-term trend in flooding over the last 80–120 years in the UK. Reed (1999) stressed that there is an urgent need for more specific (e.g. regional) studies to strengthen the understanding the climate change impacts. In this study, the effort has been concentrated on analysing the possible trends of rainfall and flow in South West England.

2. CATCHMENTS

The South West region covers 20,802 square kilometres and features over 10000 kilometres of main river. The main hydrometric networks consist of 185 flow gauging stations; 303 groundwater stations and 552 rainfall stations (Environment Agency, 1997). Some of the rainfall records trace back to 1850s. Flow gauges tend to have short history and telemetred records started around late 1950s. In this project, three representative catchments are selected. The considering factors are: record length, catchment area, hydrological response and anthropogenic activities (urbanisation, afforestation, reservoirs, drainage diversion, etc). The final three catchments chosen to represent the south-west region were River Dart at Austin’s

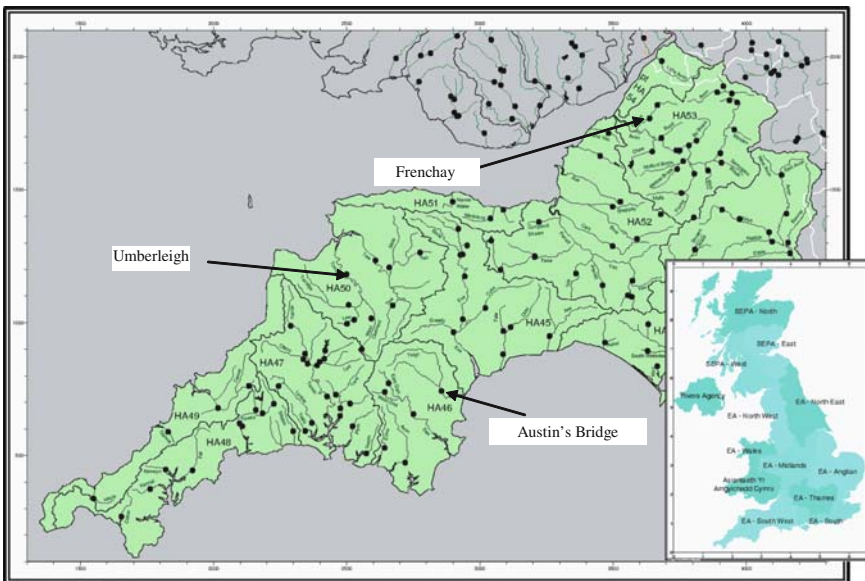


Figure 1. The selected catchments

Bridge, River Taw at Umberleigh and Frome at Frenchay. The River Taw at Umberleigh and River Dart at Austin's Bridge were chosen primarily for their less urbanised characteristics and large catchment size. Meanwhile, the River Frome (Bristol) at Frenchay lies in the north-east of the region. It was chosen to provide good coverage of whole south-west and for its record length. However, it may not have been the best catchment due to the possibility of effects of urbanisation in Bristol. The three catchments represent different orographical location, catchment area (248, 152 and 826 sq km), mean annual rainfall (1771, 792 and 1153 mm), mean flow (11.10, 1.68 and 18.20 cumecs).

The Austin's Bridge river flow station on the River Dart is located in south Dartmoor. It has a velocity-area station with main channel approximately 30m wide. A rock step forms its stage-discharge control. This station is well rated. Though there is a reservoir, Venford, in operation, this has minor effects on high river flow records. The upper two thirds of the catchment drains moorland associated with the Dartmoor Granite while the lower third is of Carboniferous shales and sandstones. This catchment is graded as responsive and has low grade agriculture and woodland. Umberleigh, on the River Taw, is located between Barnstaple and Exeter. This catchment has rainfall and gauged flow data dated from 1958. The flow gauge is a velocity-area station with main channel of about 34m wide. Similar

Table 1. Station and catchment statistics (FEH, CD 2000)

	Austin's Bridge	Frenchay	Umberleigh
Flow Statistics (m ³ /s)			
Mean flow	11.10	1.68	18.20
Mean flow (10 ⁶ m ³ /yr)	349.0	52.9	574.0
Peak flow / date	549.7 (27 Dec 1979)	70.8 (10 Jul 1968)	644.9 (4 Dec 1960)
Highest daily mean / date	268.0 (27 Dec 1979)	53.5(18Dec 1965)	363.8 (4 Dec 1960)
Lowest daily mean / date	0.590 (27 Aug 1976)	0.075 (10 Aug 1976)	0.202 (28 Aug 1976)
Mean annual flood	229.5	35.7	247
Baseflow Index	0.52	0.40	0.47
Station and Catchment			
Characteristic			
Station level (mOD)	22.4	20.0	14.1
Sensitivity (%)	7.8	—	9.2
Catchment Area (km ²)	247.6	151.57	826.2
Maximum altitude (mOD)	604	193	604
DPSBAR. slope (m/km)	124	28.7	106.9
SAAR (mm)	1771	792	1153
URBEXT 1990	0.004	0.071	0.0007
Median annual Max 2-day rainfall (mm)	83.1	46.9	51.6
Gauged flows and rainfall	1958–1999	1961–1999	1958–1999

DPSBAR – Mean of all inter-nodal slopes for the catchment. Characterises overall steepness

SAAR – Standard period (1961–1990) average annual rainfall (mm)

URBEXT 1990 – Extent of urban and suburban land cover (1990)

to Austin's Bridge, it also has a rock step downstream forming the control. This catchment has a good rating and the data is reasonably reliable. This is a large rural catchment that drains Dartmoor (granite) in south and Devonian shales and sandstones of Exmoor in the north. The central area of the catchment is underlain mainly by Culm shales and sandstones (Carboniferous). River Frome (Bristol) at Frenchay is located on the suburb of Bristol and is more urbanised than the other two catchments. This station holds gauged flows and rainfall data from 1961–1999. The station in Frenchay has trapezoidal critical depth flume. This flume is designed on a basis of pre-urbanisation flow estimates. During 1965 and 1968, this site was swamped in two respective storms. The station lies in a region of complex geology, the eastern and central catchment is dominated by sandstones of the Coal Measures and Keuper Marl. The west is less permeable with Keuper Marl and Liassic clays. Superficial deposits can also be found in the west from meltwater gravels and terraces (Grevatt and Kohl, 2001). Further details on these three catchments can be found in Figure 1 and Table 1.

3. TRENDS OF RAINFALL AND FLOW

Hydrological data series contain significant high frequency contents and it is important to remove these high frequency elements to reveal the true underline low frequency trends embedded in the data. To achieve this, a linear low pass filter commonly used in the time series analysis is used in this study to convert one time series $\{x_t\}$ with high frequency, into another series $\{y_t\}$ in low frequency (Chatfield, 1996).

$$(1) \quad y_t = \sum_{r=-q}^{+s} a_r x_{t+r}$$

where $\{a_r\}$ is a set of weights. In order to smooth out local fluctuations and estimate the local mean, we should choose the weights so that $\sum a_r = 1$. The order and weights of this low pass filter should be designed to reflect the frequency contents of the data series (Spectral analysis and autocorrelation), hence different filters should be used for rainfall, flow in different temporal resolution and catchment sizes. Detailed design process on this low pass filter has been described by Chatfield (1996). In practice, moving averages are often symmetric with $s = q$ and $a_j = a_{-j}$. In this study, a simple symmetric smoothing filter is used with $a_r = 1/(2q+1)$ for $r = -q, \dots, +q$, and the smoothed value of x_t is given by

$$(2) \quad Sm(x_t) = \frac{1}{2q+1} \sum_{r=-q}^{+q} x_{t+r}$$

After a series of computational analysis, $q=6$ is chosen for both rainfall and flow data series.

According to the climate model from the Hadley Centre, the climate change in the South West region will not alter its annual average rainfall noticeably. However,

its simulations pointed to possible changes in rainfall patterns and seasonality with higher rainfall intensity and volume in winter and reduced rainfall in summer (Tompkins 2001). According to the principles of rainfall and runoff process, it is expected that more floods in winter under climate change should be observed till now or in the future.

3.1. Seasonal Trends of Rainfall

Daily rainfall data from 9 raingauges are converted using Thiessen Polygon method into catchment area rainfall depth accumulated into two seasons: winter (December – February) and summer (June–August). The changes in other seasons are in smaller scales and not presented in this paper. The data series are then processed with the low pass filter to remove the high frequency elements as illustrated in Figure 2. The results are as expected and follow the simulation from the Hadley climatic models. All the catchments show some degree of increased rainfall depth in winter and slight change of rainfall in summer and this indicates that these changes are of regional characteristics. However, these trends are not uniformly distributed in three catchments. Frenchay and Austin's Bridge have more significant upward trends in winter rainfall (Austin's Bridge 16mm/decade and Frenchay +20 mm/decade). Generally, the rates of rainfall change in summer are less severe in comparison with those in winter. In Umberleigh catchment which has a medium mean annual rainfall of 1153mm, no significant trends are observed both in winter and summer.

3.2. Seasonal Trends of Mean Flow

Surface runoff, or river flow from a catchment is closely linked with rainfall, in addition to catchment and other meteorological factors. Generally, the trend patterns of river flows should follow the trends in rainfall. The mean seasonal flow rates in winter and summer are derived from daily mean flow records and are used to represent the flow volumes in these seasons (the actual volume of runoff can be calculated by the seasonal mean flow $\times 3 \text{ month} \times 30 \text{ day} \times 24 \text{ hour} \times 3600 \text{ seconds}$). After the low pass filtering, winter and summer seasonal mean flow series are presented in Figure 3. Generally, as expected, the seasonal mean flow patterns follow those in seasonal rainfall depth in all three catchments with more winter flows and less change in summer flows. The marked downward trend in Austin's Bridge and Frenchay summer mean flow may indicate the influence of anthropogenic activities in those catchments and/or the higher rate of evapotranspiration caused by higher temperature.

3.3. Seasonal Trends of Peak Flow

The maximum flows, or peak flows are very useful for hydraulic engineering practice, especially in flood defence. In contrast to flow volume (or mean flow rate), peak flows are not only influenced by the catchment characteristics, but also the

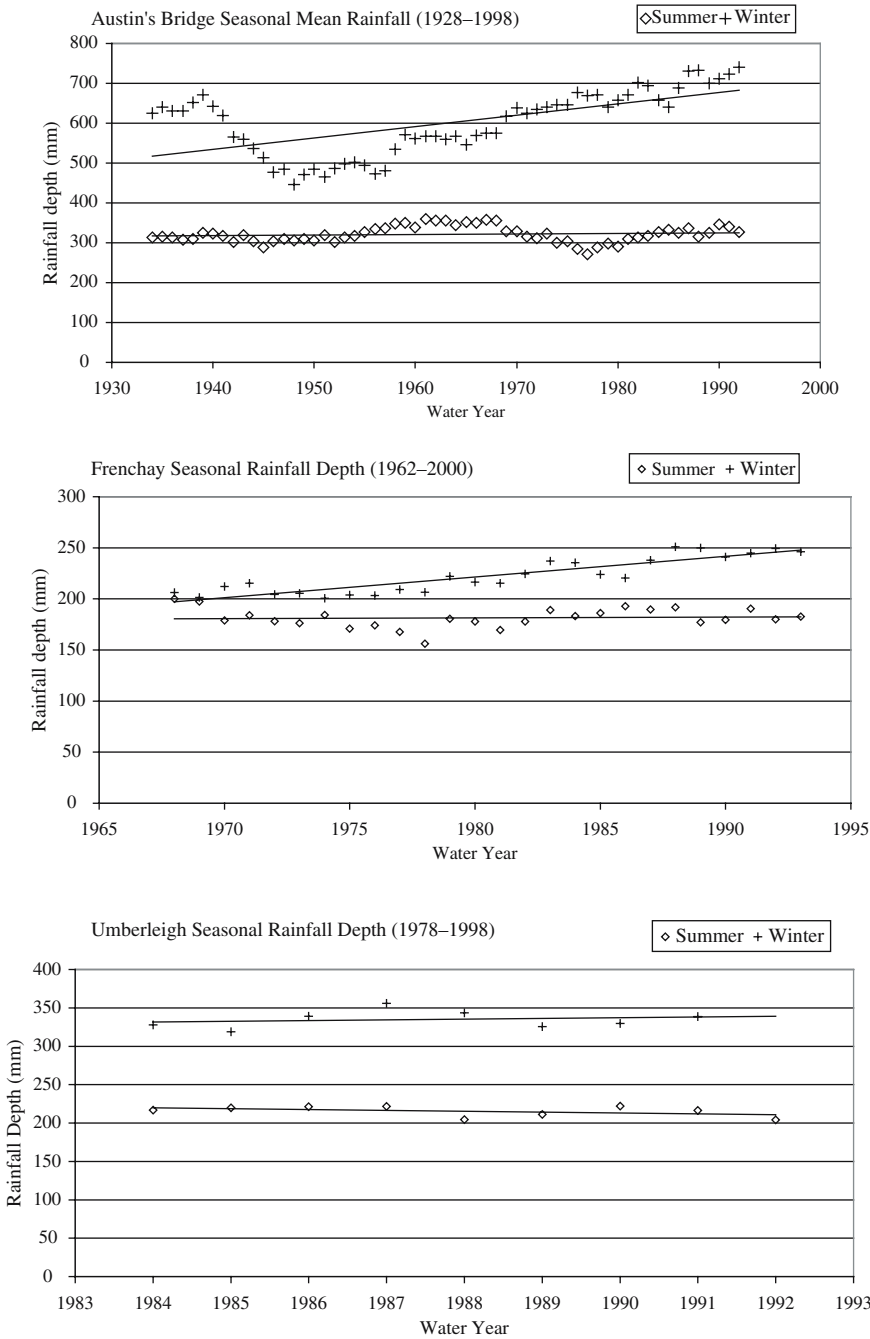


Figure 2. Total rainfall by seasons

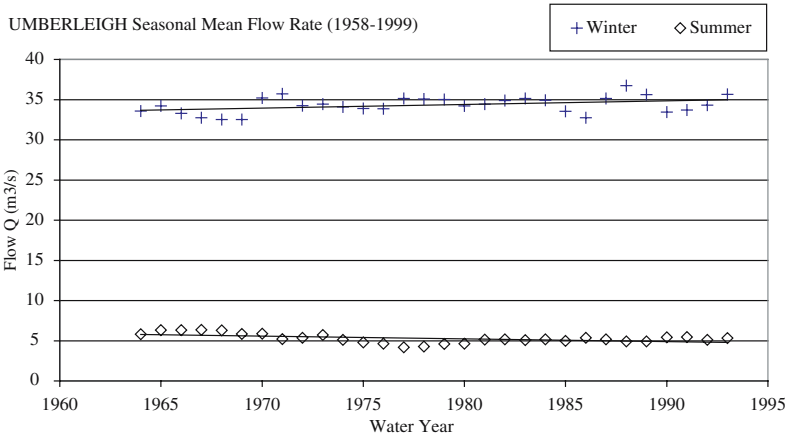
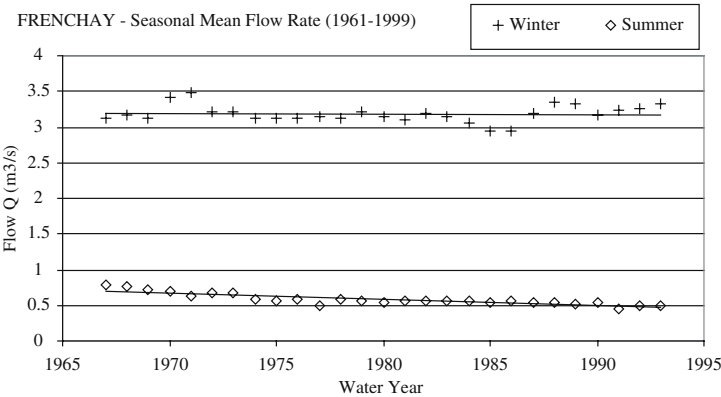
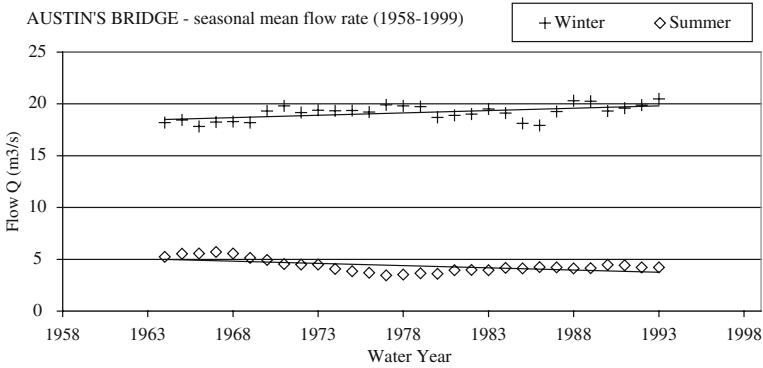


Figure 3. Mean flows by Seasons

precipitation patterns. Seasonal total runoff in a catchment is usually in line with seasonal rainfall depth and due to its instantaneous nature, the peak flow may not follow the total seasonal rainfall pattern. For example, the same amount of rainfall of 100 mm could generate very different peak flows if the rain is distributed over 24 hours or 48 hours. In this study, three peak flows are selected in these catchments: annual peak flow, winter peak flow and summer peak flow (For Frenchay, only annual peak flow series are assembled due to the data availability problem in that catchment). Again, after low pass filtering, these peak flows are illustrated in Figure 4 and it is interesting to note that these peak flows are generally in downward trends not only in summer, but also in winter and annual basis. This result has serious implications for flood defence practice if the planning and operation of our defence systems are based purely in peak flows. It is not clear at this stage as to the reasons for the downward trends in peak flows. This could be caused by the land use change (for example, increased storage capacity of the land could slow down the runoff process) or the rainfall pattern change (rainfall with longer duration).

3.4. Trends of Return Period of Annual Maximum Flow

Hydraulic projects are designed for the future and engineers are usually uncertain as to the precise conditions to which the works will be subjected. This is because that the exact sequence of river flow for future years cannot be predicted and it is usually assumed that the future hydrological processes will follow the same pattern as their past. A widely used data set for probability analysis is the annual maximum flow series (or the annual flood series). Several standard frequency distributions could be used to fit the data series, such as Gumbel, Pearson III, etc. Although there is no real proof of their validity, these distributions have been widely used in practical engineering projects, therefore it is important to identify the trends of these distributions with time. Both Log Pearson III and Gumbel distributions have been adopted in the study and only the results from Pearson III curves are presented in Figure 5 due to the similar outcomes from both distributions. Generally there are downward trends of return period curves in all three catchments. In Frenchay catchment, 100 yr flood has been changed from 85 m³/s to 45 m³/s from 1961–81 period to 1981–97 period. The changes in Umberleigh is less significant but still evident (from 850 m³/s in 1958–78 to 620 m³/s in 1978–99). The changes in Austin's Bridge is much smaller than the other two. Clearly, the change of return period curve will have significant influence over the operation and planning of existing and future water resources systems.

3.5. Evaluating the Goodness of Fit

Although a visual examination of the fitted trend curves provides an important indication of the tendencies of the related hydrological variables, some statistical measures to judge the goodness of fit of these curves are useful tools in quantifying the uncertainties in drawing our conclusions, which are residuals,

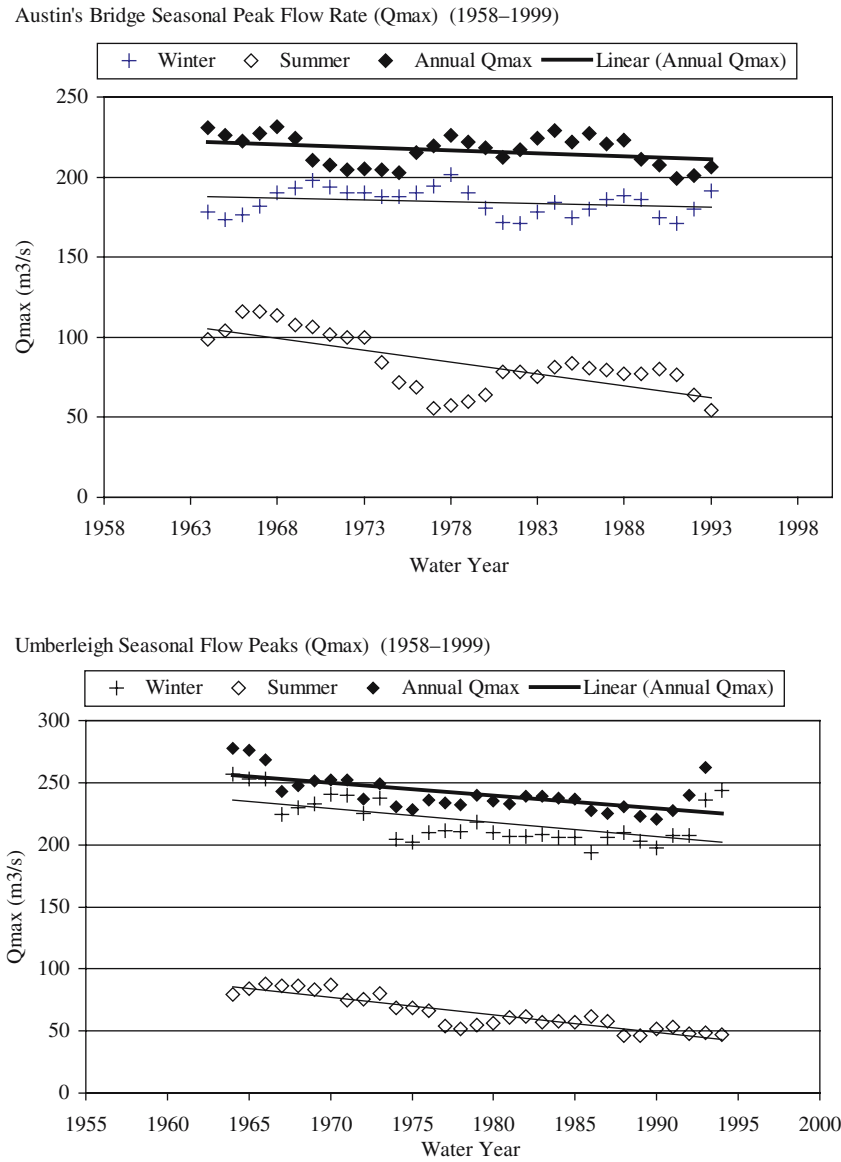


Figure 4. Seasonal and annual peak flows

goodness of fit statistics, and confidence bounds. These measures can be grouped into two types: graphical and numerical (Matlab, 2004). The residuals are graphical measures, while the goodness of fit statistics and confidence bounds are numerical measures. Generally speaking, graphical measures are more beneficial

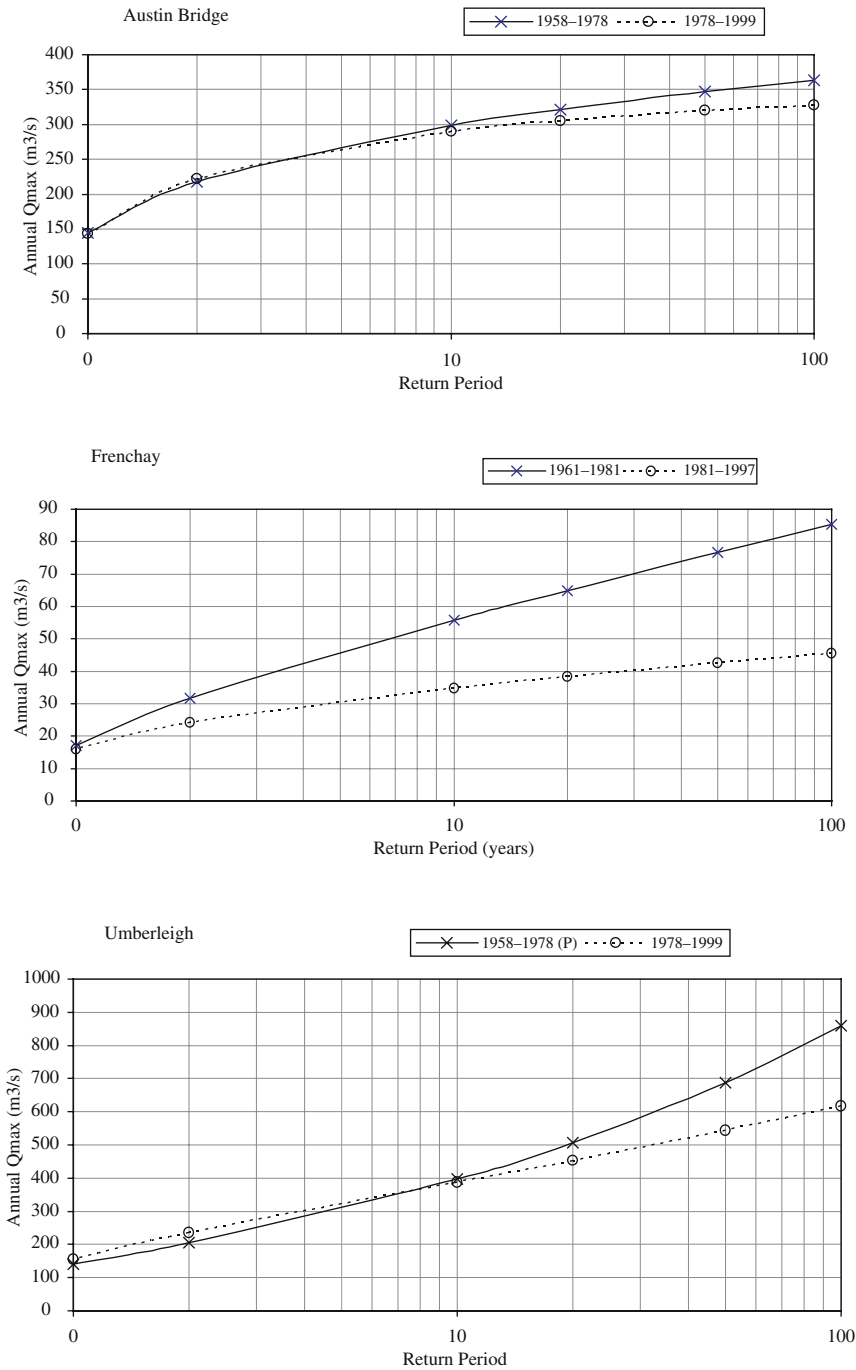


Figure 5. Peak flow distributions with moving time frames

than numerical measures because they allow the view of the entire data set at once, and they can easily display a wide range of relationships between the model and the data. On the other hand, the numerical measures are more narrowly focused on a particular aspect of the data and often try to compress that information into a single number. However, due to the dominance of the stochastic components in hydrological variables, it is difficult to reveal the patterns by graphical display of residual time series, hence in this paper, goodness of fit statistics are mainly used for the fitting assessments: R-square, t-test of slope, and F-test of the whole model.

The t-test of slope is based on hypothesis test: The null hypothesis specifies that there is no linear relationship between the dependent variable and independent variables, which means that the slope is zero. Here two tails test is used to determine whether there is sufficient evidence to infer that a linear relationship exists. However, F-test in the analysis of variance can combine all t-tests into a single test and is a good indicator of the whole fitting, which is a useful feature for multiple regression, especially when multicollinearity exists, since multicollinearity does not affect the F-test, nor does it inhibit us from developing a model that fits the data well (Keller, 2001). For simple linear regression curve fitting, the F-test is identical to the t-test, due to the fact that there is only one independent variable. Due to its longer recorder length, only results from Austin's Bridge catchment is presented in this paper, which has a better chance to pass the hypothesis tests than other two catchments. The test of slope addresses only the question of whether there is enough evidence to infer that a linear relationship exists. On the other hand, R-square or coefficient of determination can be used to check the strength of that linear relationship. R-square measures the proportion of the variation in the dependent variable that can be explained by the variation of the independent variable.

The statistics of those measured are summarised for Austin's Bridge as follows,

1) Total rainfall by seasons:

Summer Curve: $y = -101.7 + 0.215\text{year}$, $R^2 = 0.0016$, $t \text{ stat} = 0.3$,

P-value = 0.74, F stat = 0.11

Winter curve: $y = -4221 + 2.46\text{year}$, $R^2 = 0.051$, $t \text{ stat} = 1.9$,

P-value = 0.059, F stat = 3.68

It is interesting to note that the total rainfall in summer is increasing by 0.2mm/year but in winter, the increment is 2.46mm/yr (12 times that of the summer). The variations caused by the trends are only 0.16% (Summer) and 5.1% (winter) in the last 70 years in comparison with the natural variations, hence the climate change if exists has been playing a small role in the total variations of seasonal rainfall values. According the t-test, $t = 0.3$ (summer) and 1.9 (winter) are too low and we cannot reject the null hypothesis at a significant level of 5% (albeit the winter curve is very close at a significant level of 6%).

2) Mean flows by Seasons

Summer Curve: $y = 52.88 - 0.025\text{year}$, $R^2 = 0.026$, $t \text{ stat} = -1.05$,

P-value = 0.30, F stat = 1.09

Winter curve: $y = -151.4 + 0.086 \text{ year}$, $R^2 = 0.032$, $t \text{ stat} = 1.16$,
 $P\text{-value} = 0.25$, $F \text{ stat} = 1.34$

These statistics show more significant changes of mean flows in winter than in summer. Both curves failed the t-test and F-test at significant levels of 5% and 10%.

3) Seasonal and annual peak flows

Year: $y = -339.0 + 0.223 \text{ year}$, $R^2 = 0.006$, $t \text{ stat} = 0.48$,
 $P\text{-value} = 0.63$, $F \text{ stat} = 0.23$

Summer: $y = 600.6 - 0.290 \text{ year}$, $R^2 = 0.037$, $t \text{ stat} = -1.24$,
 $P\text{-value} = 0.22$, $F \text{ stat} = 1.56$

Winter: $y = -743.6 + 0.423 \text{ year}$, $R^2 = 0.016$, $t \text{ stat} = 0.81$,
 $P\text{-value} = 0.42$, $F \text{ stat} = 0.66$

These statistics show more significant changes in winter than in summer as well. All curves failed the t-test and F-test at significant levels of 5% and 10%.

4) Return periods

Year 58-78: $R^2 = 0.978$, at 100 year return period, the confidence band is $370 \pm 55 \text{ m}^3/\text{s}$ at a significant level of 5%.

Year 78-99: $R^2 = 0.965$, at 100 year return period, the confidence band is $325 \pm 60 \text{ m}^3/\text{s}$ at a significant level of 5%.

Hence, the difference of $45 \text{ m}^3/\text{s}$ is not beyond the confidence band.

From the above, although all tests failed to reject the null hypothesis at the significant level of 5%, it is important to note that these statistical hypothesis tests use a standard null hypothesis that there is no trend. The purpose of the tests is to reject (or accept) it. There are commonly two errors in hypothesis testing: Type I can be made when we reject a hypothesis when it should be accepted. If, on the other hand, if we accept a hypothesis when it should be rejected, a Type II error has been made. In either case, a wrong decision or error in judgment has occurred. In order for decision rules (or tests of hypotheses) to be good, they must be designed so as to minimise errors of decision, which is not a simple matter, because for any given sample size, an attempt to decrease one type of error is generally accompanied by an increase in the other type of error (Spiegel and Stephens, 1998). In practice, one type of error may be more serious than the other, and so a compromise should be reached in favour of limiting the more serious error. If we accept that no climate trends can be found from these data series based on our hypothesis tests, there is a real danger that a Type II error could be made and the consequence of this error could be quite serious in future water management activities. Since the only way to reduce both types of error is to increase the sample size, this problem will be with us for a quite long time in future climate trend studies.

4. DISCUSSION AND CONCLUSIONS

The three catchments are fairly distributed in the South West to represent different hydrological characteristics with a wide range of annual rainfall and runoff characteristics. From the results above, it has been found that there are general trends in

seasonal rainfall, seasonal mean flow and peak flows in all catchments. The increase of rainfall in winter in the region is more evident in comparison to the change of rainfall in summer, especially in Frenchay catchment where the trend in summer is almost illegible. This pattern fits well to the current climatic model's simulation. Runoff patterns generally follow rainfall and it is clear that the increase in winter and decline in summer are mapped well from rainfall to river flows. One interesting finding in Austin's Bridge and Frenchay catchments is that an almost stationary rainfall series in summer is corresponding to a marked downward trend in runoff, indicating a gradual change of rainfall and runoff characteristics, possibly caused by land use change, other anthropogenic activities or increased evapotranspiration due to higher temperatures.

An unexpected outcome from the study is the disparity between the increased mean flow and peak flows in winter seasons. This could have serious implications to flood defence systems, especially when all three catchments depict similar trends in mean flow and peak flows. It is known that regional flood patterns could be greatly influenced by local anthropogenic activities. Most land use changes would have an important effect on flood. Urbanisation has been widespread and dramatic since the Industrial Revolution in the UK. A variety of farming practices applied to agricultural lands also altered the hydrological characteristics of streams. This is particularly important in the SW peninsula. [Kundzewicz and Kaczmarek \(2000\)](#) stated that deforestation and urbanisation could lead to reduction of the storage volume and higher values of runoff coefficient. However, it is extremely difficult to segregate and quantify these individual factors. [Potter \(1991\)](#) found that for the East Branch of the Pecatonica River in southwestern Wisconsin, a decrease in flood peaks did not appear to be due to climatic variations, instead, they appear to have resulted from the adoption of various soil conservation practices, particularly those involving the treatment of gullies and the adoption of conservation tillage. On the other hand, [Hiscock et al \(2001\)](#) analysed the flow records of the Rivers Bure, Nar and Wensum in eastern England and found that in the study area, despite changes in water resources use and catchment characteristics since the beginning of the 20th century, such as the ending of water milling and increased land drainage and arable farming, rainfall-runoff modelling over the period 1964-1992 showed that the relationship between rainfall and runoff has remained essentially unchanged in the three study rivers. Another factor is the change of rainfall patterns temporally and spatially. Modern remote sensing devices, such as weather radar, are able to provide much higher resolution rainfall data in time and in space than traditional rain gauge networks, however, such data are underused at the moment in climate change research.

The change of return period curves poses a fundamental problem in the design and operation of water resources systems. Although the true frequency distributions of peak flows are impossible to obtain in practice, these curves are only approximate to the true distributions based the samples, hence the longer the records, the better estimation of these artificial distribution curves. However, if trends are found in these distribution curves, longer records may not produce a better return period

curve to be used in our designs, since the changes in the frequency distribution with time has rendered the early records less representative to the future. Another problem is the criterion for assessing the flood severity. With this increased flow volume and reduced peak flows, the traditional way of using return periods of flood peaks to describe floods may face new problems, as highlighted by the recent floods in England (for example, a flood may have a return period of 100 yr in term of peak flow, 200 yr of stage and 300 yr of volume). A multi variable flood frequency assessment may be the way forward. Despite the research work so far (Sackl and Bergmann, 1986, Feng et al, 2000), the practical applications of this technique under climate change influence still need further research.

Impact of climate change on hydrological systems is a very complicated process, especially for river flows and there is a great demand for improving our understanding on this important issue from the water industry, regulatory authorities, central government, and not the least, the general public. This study provides some detailed regional and seasonal variations on trends of rainfall and flows in South West England. It should be noted that due to the short durations of the records and only three catchments analysed, there is a huge uncertainty in extending the trends into the future. Further work using sub-daily data and weather radar for spatial analysis, in addition to land use change in the region will be our next challenge to take.

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CHAPTER 16

PROPAGATION OF DISCHARGE UNCERTAINTY IN A FLOOD DAMAGE MODEL FOR THE MEUSE RIVER

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Abstract: Uncertainty analysis plays an important role in the decision- making process. It can give decision makers better understanding in how different measures will affect the whole river system. Thus it helps decision makers to make a sound choice among measures in a more systematic manner. In case of flood damage reduction projects, uncertainty analysis helps to evaluate the main decision criterion – expected annual damage. The aim of this paper is to investigate the propagation of discharge uncertainty, which is one of the main uncertainty sources in a damage model, into expected annual damage. The discharge uncertainty considered includes model uncertainty (choice of different probability distributions) and sampling errors due to finite gauge record lengths. The calculated uncertainty in the discharge varies between 17 percent for a return period of 5 year and 30 percent for a return period of 1250 year. A first order method is used in this paper to explore the role of discharge uncertainty in the expected annual damage model. The results from the damage model indicate that both model uncertainty and sampling errors are important, with the latter being somewhat more important. The Log-Pearson Type 3 gives a much smaller uncertainty range of the expected annual damage than the other three distribution models used. The uncertainty is aggravated when propagated into the damage results. The uncertainty in the damage reduces a great amount when the sample size increases to $n = 80$. The results derived from the first order method in fact give two bounds of uncertainty, which is an overestimate in this case

Keywords: flood frequency analysis, discharge, expected annual damage, first order analysis, uncertainty, Dutch Meuse River

1. INTRODUCTION

Flood damage estimation plays an important role in decision making for river basin management. Recently, in the Dutch part of the Meuse River in Europe, the serious 1993 and 1995 floods stimulated the start of a new project “De Maaswerken”, which mainly aims to alleviate the effects of floods. One of the main decision criteria in the evaluation of this project is the expected annual damage. Due to the growing importance of uncertainty in decision making, it is necessary to investigate the uncertainty sources in the damage model and how they are propagated into the final damage results.

In general, there are several sources of uncertainty in a model. Important sources include data uncertainty, model uncertainty and parameter uncertainty. For more detailed information, see e.g. the taxonomy of uncertainty of [Suter et al. \(1987\)](#). The uncertainties in a damage model originate from e.g. the river discharge, river cross-section data, channel resistance, schematization of rivers, spatial resolution and damage functions. As a preliminary analysis, this paper only considers the effect of river discharge uncertainties on the damage model applied to the Dutch Meuse River. The effects of other uncertainties are described in other papers, for example the effect of spatial resolutions on flood damage is explored by [Xu et al. \(2002\)](#).

The uncertainties in river discharge consist of uncertainties due to the choice of different probability distributions, which are used to describe flood frequency, and parameter uncertainties caused by sampling errors due to finite gauge record lengths (annual maximum discharges). The availability of data is an important aspect in flood frequency analysis. The estimation of the exceedance probability of floods is an extrapolation based on limited available data. From a statistical point of view, the larger the available data set, the more accurate the estimates of exceedance probabilities of floods will probably be.

The uncertainties in river discharge have already been explored by Wood and Rodriguez-Iturbe ([1975](#)), [Stedinger \(1983\)](#), [Al-Futaisi and Stedinger \(1999\)](#). They proposed different methods to take into account the uncertainty in river discharge. However, the propagation of discharge uncertainty into damage models has not been often investigated. [Beard \(1997\)](#) and [Stedinger \(1997\)](#) used Monte Carlo Methods to investigate the role of uncertainty in the expected annual damage from which the results are difficult to interpret because they do not come in a nice analytical form. They mainly emphasized the advantages and disadvantages of different parameter estimators while they ignored the effects of different probability distributions.

The objective of this paper is therefore to investigate the effects of both probability distributions and sample size (the length of annual maximum discharges) on discharge and damage results quantitatively, and obtain insight about relative contributions of uncertainty. This is done by a first order method which is used because it is simple, it can save time, and the results come in a nice analytical form. Section [2](#) describes the methods used, including the first order method. Section [3](#) gives the application of the methods to the Dutch Meuse River. Section [4](#) shows the uncertainty effects on the model results and the conclusions are given in Section [5](#).

This paper gives some ideas of how the uncertainty will affect the decision criterion, here the expected annual damage in evaluating the different measures and thus support decision makers to make sound decisions.

2. FLOOD DAMAGE AND UNCERTAINTY

2.1. Flood Frequency Analysis

Flood frequency analysis is an essential part when the expected annual damage is calculated. The primary objective of flood frequency analysis is to relate the magnitude of extreme events (discharge) to their frequency of occurrence through the use of probability distributions (Chow et al., 1988). Flood frequency analysis is often used to calculate the expected annual damage, design flows for dams, bridges, culverts, flood control structures, flood plain management etc. The basic assumptions of flood frequency analysis are:

- 1) Historical events represent future events
- 2) Events are independent
- 3) Distributions fit entire data sets and future data
- 4) Space and time independency

In fact some of them are rather simplifications, for example when climate change and land use change play a role in flood frequency analysis. In this paper, our key point is to explore the role of uncertainty in the estimation of flood flows for different frequencies and in the estimation of the expected annual damage. Therefore, the main features in flood frequency analysis are described, namely extreme value distributions, parameter estimations, estimations of T-year event discharges and confidence intervals for T-year event discharges from subsection 2.1.1 to subsection 2.2.4.

2.1.1. Extreme value distributions

In flood frequency analysis, an important aspect is to choose a certain distribution that will be used to describe flood flows. The most often used are the Lognormal distribution (LN), Gumbel Extreme Value distribution (GEV), Pearson Type 3 distribution (P3) and Log Pearson Type 3 distribution (LP3) (Kite 1977; Chow et al., 1988). The choice of the distribution is one of the main sources of uncertainty because it is unknown which of the above distributions is the most appropriate distribution for flood flows. This is important because the sample events available are usually for relatively low return periods (i.e. around the center of the probability distribution) while the events for which estimations are required are associated with large return periods (i.e. in the tail of the distribution) (Kite 1977; Van Noortwijk et al., 2003). Many probability distributions have very similar shapes in their centers, but differ widely in their tails. It is thus possible to fit several distributions to the sample data and end up with several different estimates of the T-year event discharge. Some goodness-of-fit tests like the Chi-squared test or the Kolmogorov-Smirnov test can be used in this case. However, this does not solve the basic problem

of different tails (Kite 1977). As (Van Noortwijk et al. (2003)) mentioned, different distributions usually lead to different extrapolated values and the goodness-of-fit tests for selecting the appropriate distribution are often inconclusive.

In this paper, to get the idea of how much the uncertainty is propagated into the EAD and how much differences exist because of the choice of probability distributions and the sample size, four different distributions are investigated and compared.

2.1.2. Parameter estimations using conventional method of moments

When fitting a probability distribution to data sets, an estimation of the parameters of that distribution is needed. Several approaches are available for estimating the parameters of a distribution, such as the conventional method of moments, maximum likelihood estimators and the Bayesian estimation procedure. The advantages and disadvantages of these methods have been discussed by Al-Futaisi and Stedinger (1999) and (Stedinger (1997)). Besides these methods, a current and satisfactory approach called L-moments is used in the United Kingdom (Flood Estimation Handbook, 1999). The advantage of the L-moment approach is that its estimators are almost unbiased, so it can provide simple and reasonably efficient estimators of a distribution's parameters. However, the choice of the parameter estimation method is not the authors' focus. In this paper the conventional method of moments is used.

The method of moments states that the k -th sample moment about the origin is an unbiased estimator for the k -th population moment. Thus in order to estimate the parameters of a probability distribution, it is assumed that the first and second population moments about the origin equal to the first and second sample moments:

$$(1) \quad \mu_1(0) = M_1(0) \quad \mu_2(0) = M_2(0)$$

Here $\mu_1(0)$ and $\mu_2(0)$ are the first and second population moments about the origin respectively and they are functions of the population mean μ and standard deviation σ , $M_1(0)$ and $M_2(0)$ are the first and second sample moments respectively (Shahin et al. 1993).

2.1.3. Estimation of T-year event discharges

After the estimation of the distribution parameters, the T-year event discharges need to be calculated. A T-year event discharge is a discharge for a specific exceedance probability. (Chow et al. (1988)) expressed the T-year event discharge as:

$$(2) \quad X_T = \mu + K_T \sigma$$

Here K_T is a frequency factor that is a function of the return period and the distribution parameters. (Shahin et al. (1993)) has given the detailed information about the calculations of K_T . The event magnitude X_T can be estimated as soon as the mean μ and standard deviation σ of the underlying probability distribution are estimated from Equation (1).

2.1.4. Confidence intervals of T -year event discharges

The common way to express the uncertainty in the T -year event discharges is to estimate the confidence intervals. According to [Shahin et al. \(1993\)](#), the confidence intervals for the T -year event discharge X_T are:

$$(3) \quad X_T \pm zS_T$$

If the probability distribution is lognormal, z is taken from the table of the standard normal distribution assuming a certain confidence level (e.g. 95%). For GEV, P3 and LP3 distributions, z can be taken from the Student's t -table.

In Equation (3), the standard error S_T is a measure of the variability of the resulting T -year event discharges. Equations of S_T for different distributions are given by [Shahin et al. \(1993\)](#).

2.2. Expected Annual Damage (EAD)

The U.S. Army Corps of Engineers' framework of EAD estimation will be used and is explained below ([National Research Council 2000](#)). This approach applies to the situation where the aim is to compare different flood damage reduction measures. According to [National Research Council \(2000\)](#), EAD is the average damage determined from floods of different annual exceedance probabilities over a long period. The mathematical equation of EAD, according to National Research Council (2000), is:

$$(4) \quad EAD = \int_0^1 D(F) dF$$

Here $F = F(X \geq X_T)$ is the probability that the discharge X_T is equaled or exceeded in any given year and is the reciprocal of the return period T . $D(F)$ is the damage for a flood with annual exceedance probability F .

The procedure to estimate EAD is illustrated in Figure 1. In this figure, the solid line is for the current situation without measures and the dashed line is for the improved state after measure implementation. After a new measure has been implemented, for a given water level (Figure 1 (1)), the river channel can pass a higher discharge. Therefore, the corresponding damage is smaller. The EAD by definition is the area below the exceedance probability -damage curve in (4). The shaded area in (4) represents the annual possible savings in damages after the completion of the measures.

The EAD model used in this paper is a modified version of the INUNDA model which has been used to calculate the flood damage caused by the 1993 and 1995 floods in the Dutch Meuse River ([De Blois 2000](#)). The main difference between the EAD model and the INUNDA model is that the former uses less detailed damage functions. This is appropriate for the current research purpose.

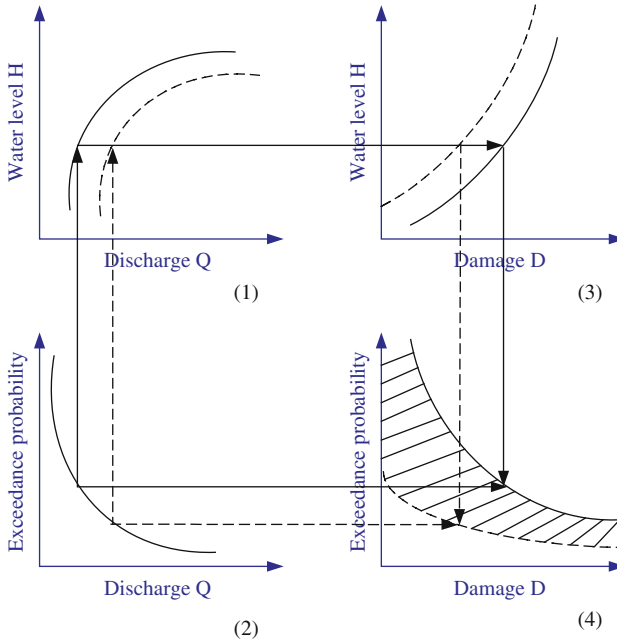


Figure 1. The procedure to estimate EAD (based on [Shaw 1994](#))

2.3. Propagation of Uncertainty

The Monte Carlo method is the often-used approach to analyze the uncertainty in model inputs and parameters. To simplify the procedure but still have a good idea of the order of magnitude of the uncertainties, a first order method is used (See e.g. [Bevington and Robinson 1992](#)).

Assume that v is a function of variables $\theta_1, \theta_2, \dots$ etc. Here θ_1 and θ_2 are inputs and parameters in a specified model.

$$(5) \quad v = f(\theta_1, \theta_2, \dots)$$

Based on Taylor series expansion, the approximation for the variance σ_v^2 becomes:

$$(6) \quad \sigma_v^2 \approx \sigma_{\theta_1}^2 \left(\frac{\partial v}{\partial \theta_1} \right)^2 + \sigma_{\theta_2}^2 \left(\frac{\partial v}{\partial \theta_2} \right)^2 + 2\sigma_{\theta_1\theta_2} \left(\frac{\partial v}{\partial \theta_1} \right) \left(\frac{\partial v}{\partial \theta_2} \right) + \dots$$

Here $\sigma_{\theta_1}^2$ is the variance of θ_1 , $\sigma_{\theta_2}^2$ is the variance of θ_2 , and $\sigma_{\theta_1\theta_2}^2$ is the covariance between the variables θ_1 and θ_2 .

If the fluctuations in θ_1 and $\theta_2, \dots$ are not correlated, the higher order terms can be neglected. Then Equation (6) reduces to:

$$(7) \quad \sigma_v^2 \approx \sigma_{\theta_1}^2 \left(\frac{\partial v}{\partial \theta_1} \right)^2 + \sigma_{\theta_2}^2 \left(\frac{\partial v}{\partial \theta_2} \right)^2 + \dots$$

In this paper, Equation (7) is used to investigate the effects of uncertainties in T-year event discharges on the damage results. Equation (7) is based on two assumptions, namely independence among variables and model linearity. Since this equation is used to propagate the discharge uncertainty into EAD, the important input here is the discharge. Additionally, the model uncertainty is investigated by comparing different distributions in calculating the damage.

3. CASE STUDY

3.1. The Meuse River

The Meuse River has a total length of about 900 km. The basin covers an area of about 33,000 km². After passing through France, Luxembourg and Belgium, the river enters the Netherlands at Eijsden, south of Maastricht (see Figure 2). The Meuse River can be subdivided into three major zones: the Lotharingian Meuse, the Ardennes Meuse and the lower reaches of the Meuse.

The Meuse River is fed by rainfall all year round. Large seasonal variations in river discharge can be observed (Figure 3). The average discharge of the river at Borgharen, which is located upstream of the Dutch Meuse River, is about 200 m³/s (Booij 2002). Most high discharges occur in winter, when evaporation levels are lowest. For example, the discharges during the 1993 and 1995 floods were about 3050 m³/s and 2750 m³/s respectively at Borgharen.

The Dutch part of the Meuse River is selected here as the case study. The subsequent Dutch sections of the Meuse include the Grensmaas, the Zandmaas and the Getijdemaas. The expected annual damage is estimated for the province of Limburg, which includes two sections of the Grensmaas and the Zandmaas. The approximate coverage of the study area is indicated in Figure 2. The total length of this area is about 175 km.

Figure 4 shows a series of annual maximum discharges from year 1911 to 1997 at Borgharen. The average annual maximum discharge is about 1450 m³/s.

3.2. Data Used

Discharge data, elevation, land use, maximum economic values and damage functions for different land use types and QH curves are used in this study. Daily discharge data at Borgharen are provided by Rijkswaterstaat for 1911–1997. The elevation and land use data are the same as those used in the INUNDA model

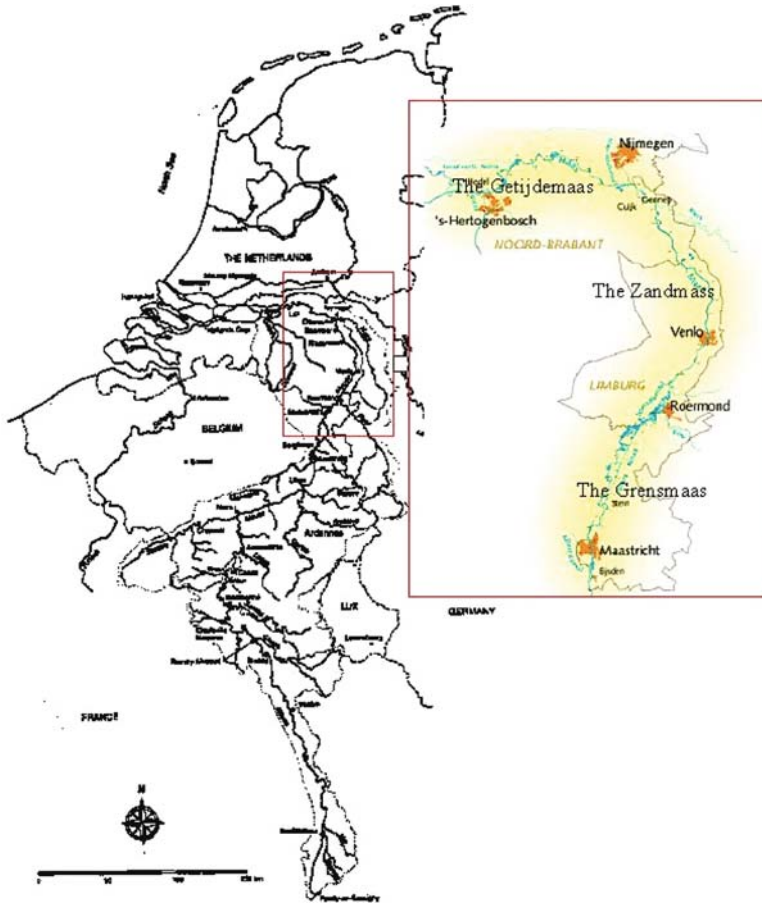


Figure 2. Catchment area of the River Meuse (Modified from [Bergel \[1997\]](#))

[\(De Blois \[2000\]\)](#). The spatial resolution of the elevation and land use data is 150 meter. The QH curves are available in 22 gauging stations along the Dutch Meuse River. The maximum economic values and damage functions for different land use types have been obtained from [Rijkswaterstaat \[2002\]](#). There are 8 types of land use, namely households, industry, construction, trade, agriculture, greenhouse, institution and water. The land use types from Rijkswaterstaat have been somewhat adjusted according to the land use types used in the INUNDA model for consistency. The damage functions are simple relations between inundation and damage for different land use types. They are either step functions or linear functions. As an example, a damage function for households is given in Figure [5](#). The damage factor in this figure is the damage expressed as a fraction of the maximum economic value for a certain inundation level.

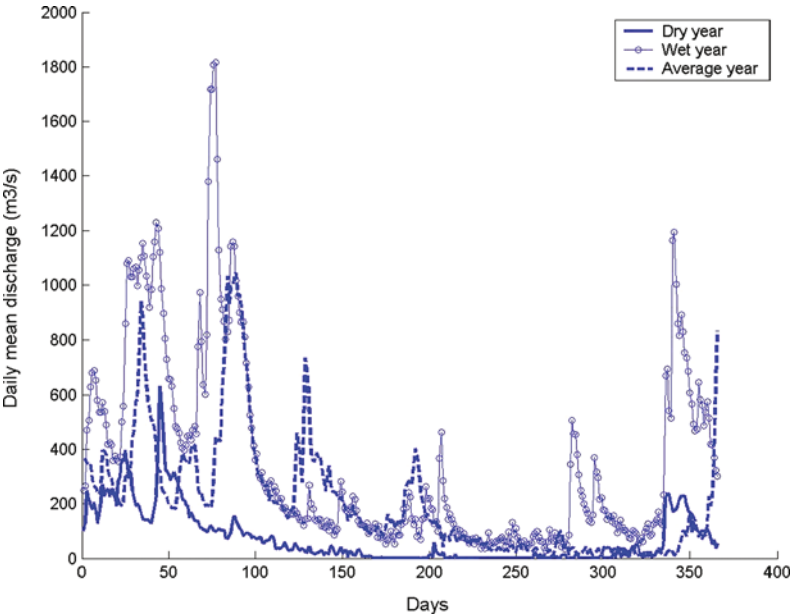


Figure 3. Daily average discharges at Borgharen

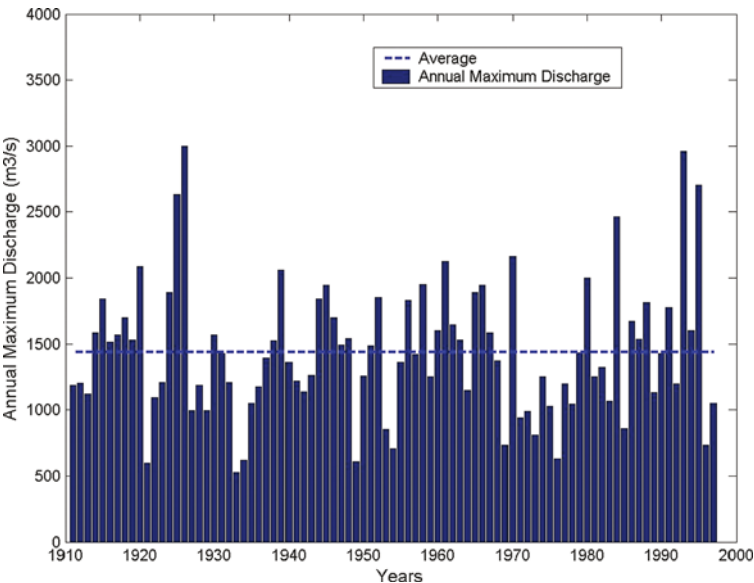


Figure 4. Annual maximum discharges at Borgharen

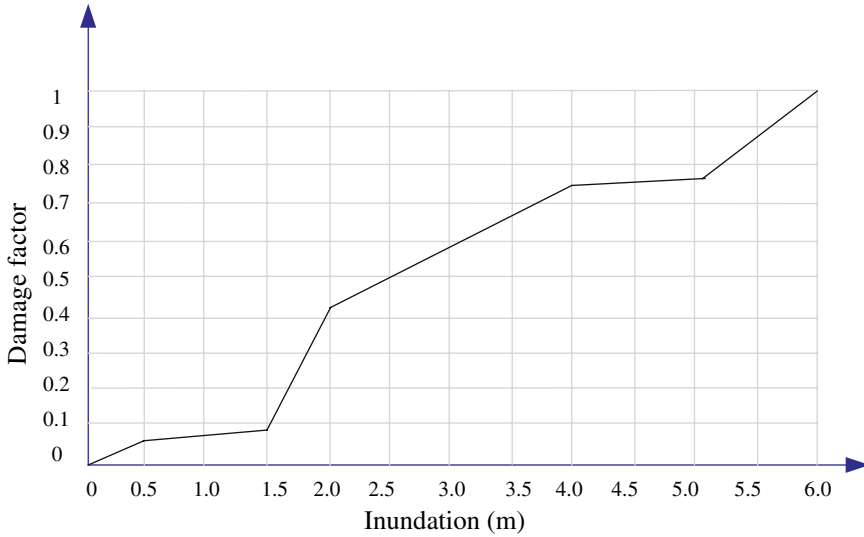


Figure 5. Example of a damage function for households

4. MODEL RESULTS AND DISCUSSION

4.1. Uncertainty Analysis of T-year Event Discharges

As mentioned in Section 2.1.1, the main difference among distributions can be found in their tails. Figure 6 shows the annual exceedance probability — discharge relationships for the four distributions considered. It is clearly shown in this figure that for a small probability (tails), the P3 model and the LP3 model resulted in much smaller discharges than the other two models while the LN model and the GEV model have relatively comparable results.

4.1.1. Effects of different distribution models

First the results are given under the assumption that the flood frequency obeys the LN model. Annual maximum discharge data for 1911–1940 (sample size $n = 30$) are used. The relationship between the discharges and return period and the related uncertainty according to the LN model is shown in Figure 7 given a confidence level of 95%.

Figure 7 shows that the uncertainty due to the natural variability can be quite high. The higher the return period, the higher the uncertainty for a T-year event discharge. Take the example of the 5-year return period event. The average discharge is about $1820 \text{ m}^3/\text{s}$ with uncertainty bounds from $1500 \text{ m}^3/\text{s}$ and $2130 \text{ m}^3/\text{s}$, which is approximately 17% uncertainty involved. For the 1250-year return period, the average discharge is $4180 \text{ m}^3/\text{s}$ with an uncertainty range around 30%. Note that the discharge for the 1250-year event calculated ($4180 \text{ m}^3/\text{s}$) is much higher than the value given by Rijkswaterstaat (2000) of about $3800 \text{ m}^3/\text{s}$ because of the effect

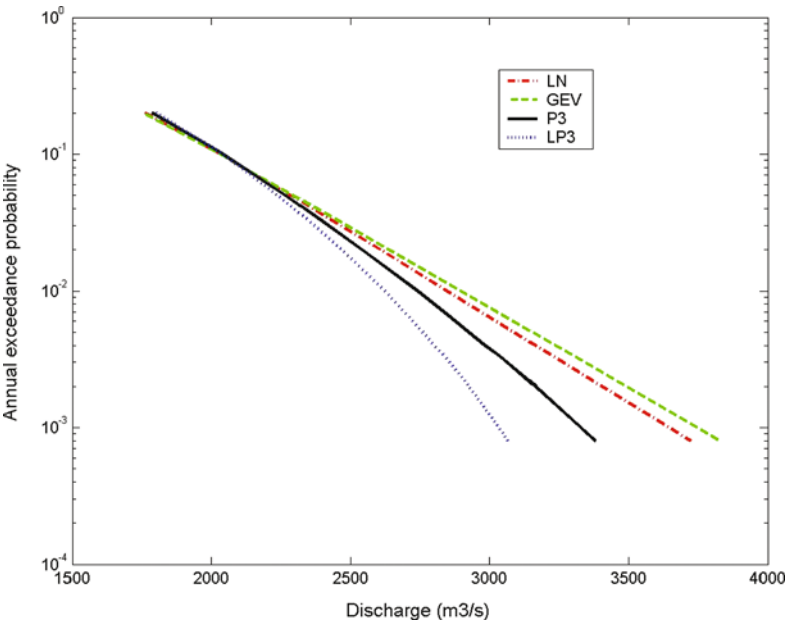


Figure 6. Discharges vs. exceedance probability for the four distribution models

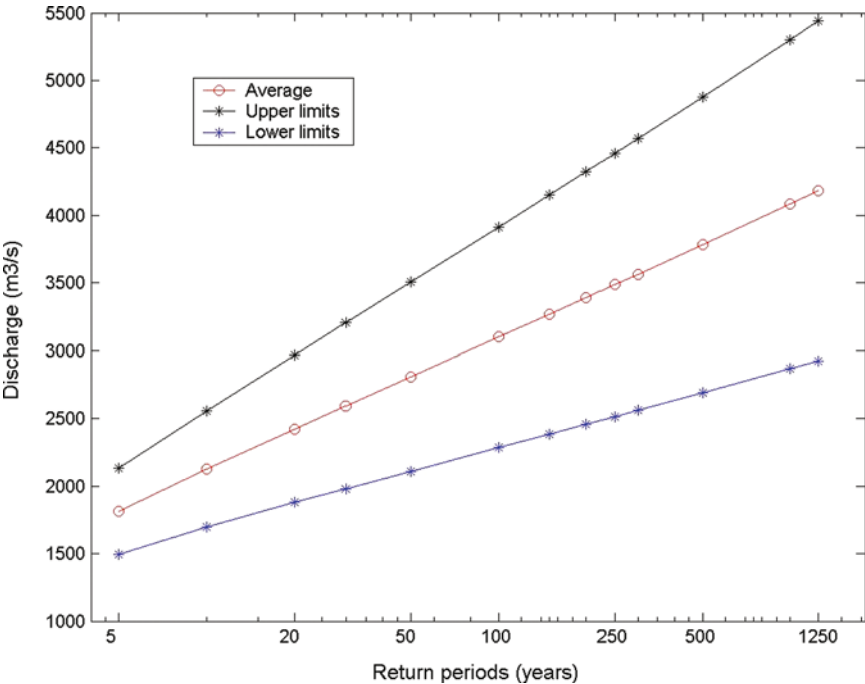


Figure 7. Return periods vs. T-year event discharges

of sample size (see Section 4.1.2). For the other three distribution models (GEV, P3 and LP3), similar results can be derived.

Figure 8 shows the uncertainty for the different distributions for a sample size $n = 30$ (1911–1940) and return periods of 50 and 1250 years. This figure shows that the average discharges for each distribution model are more or less comparable except for the LP3 model that results in smaller values. The uncertainty is different for the four distribution models. The averages and uncertainty involved in the LN model and the GEV model almost overlap while the P3 model results in the largest amount of uncertainty. Note that the results given here are without goodness-of-fit tests due to the reason that these tests still cannot solve the problem of different tails as introduced in section 2.1.1. Figure 8 also indicates that for higher return periods, the uncertainty of T-year event discharges increases due to extrapolation.

4.1.2. Effects of sample size

The relationship between discharges and return periods for different sample sizes is shown in Figure 9. This figure illustrates the average discharges for different sample sizes for the LN model. The samples are taken from the same series and start from 1911. Figure 9 shows that, for small return periods, the differences between T-year event discharges for different sample sizes are small, while for big return periods the differences are much larger. For example, for $n = 30$ and $n = 80$, the average

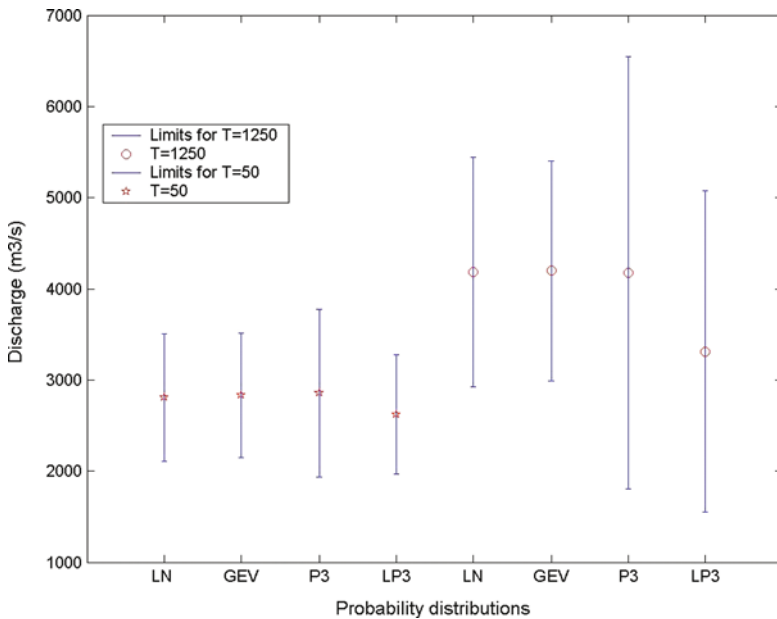


Figure 8. 95 % confidence intervals for 50- and 1250- year event discharges for four distribution models

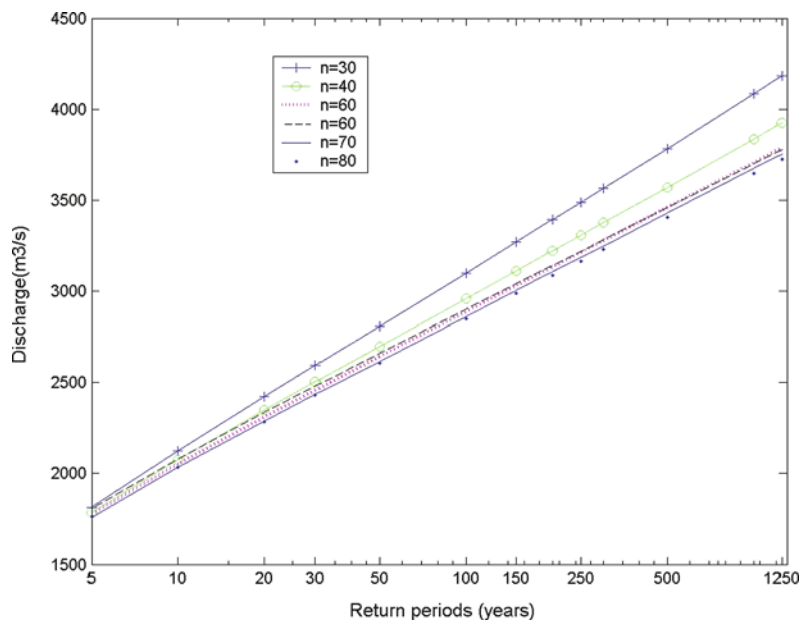


Figure 9. Discharges vs. return periods for different sample sizes

discharges for the 5 year return period are $1810 \text{ m}^3/\text{s}$ and $1760 \text{ m}^3/\text{s}$, while for the 1250 year return period the averages are $4180 \text{ m}^3/\text{s}$ and $3720 \text{ m}^3/\text{s}$ respectively. Here smaller values of T-year event discharges for larger sample sizes are due to the reduced uncertainty in discharges associated with larger sample sizes, which changes the parameter values of distribution models. This characteristic depends more on data sets.

4.1.3. Combined effects of sample size and model choice

Figure 10 gives the 1250-year event discharge for three sample sizes ($n = 30, 50$ and 80) for the four distribution models. This figure shows when the sample size becomes larger, the uncertainty bounds become smaller as well as the averages. For example for a sample size $n = 80$, for the LN model and the GEV model, the average values are $3720 \text{ m}^3/\text{s}$ and $3830 \text{ m}^3/\text{s}$ respectively, while for P3 and LP3 the values are much smaller.

4.2. Uncertainty in Damage

The uncertainty described in Section 4.1 is then propagated into the damage results. Here the first order method introduced in Section 2.3 is used to investigate the effect of the uncertainty on flood damage. Because the uncertainty considered here is mainly caused by the same natural variability in the discharge, similar conclusions

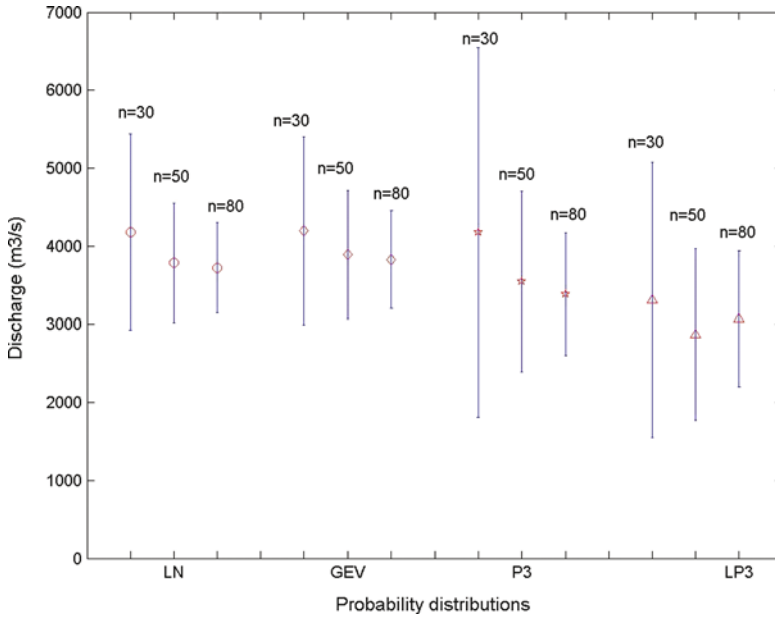


Figure 10. 95 % confidence intervals for 1250- year event discharge for different sample sizes and probability distributions

can be derived as those in Section 4.1. Figure 11 shows the relationship between the damage and return periods for the LN model for sample sizes $n = 30$ (left) and $n = 80$ (right). However, this figure tells that the uncertainty in damage could be two times as much as the uncertainty in the T-year event discharges. That means the uncertainty has been aggravated when propagated into damage results. This is because of the non-linearity of the damage model. The results indicate that if reduction of the high uncertainty in flood damage due to extrapolation for large return periods is required, for example in case of helping decision makers distinguish the different measures (Xu and Booi 2004), more data are necessary (increasing the sample size).

Figure 12 gives four graphs describing the relationship between the EAD and the sample size for different distribution models. With the increase of sample size, there is a trend that the values of EAD decrease and so does the uncertainty. From Figure 12 it is shown that the results from the LN model and the GEV model are comparable. There is more uncertainty involved in the results based on the P3 model and for this model the largest reduction of the uncertainty can be observed when the sample size increases. The EAD based on the LP3 model is smaller than the results based on the other three models.

If the sample size is changed from $n = 30$ to $n = 80$, the average values reduce by 33% for the LN model, 32% for the GEV model, 42% for the P3 model and 30% for the LP3 model. From Figure 12, it can be seen that the effect of sample

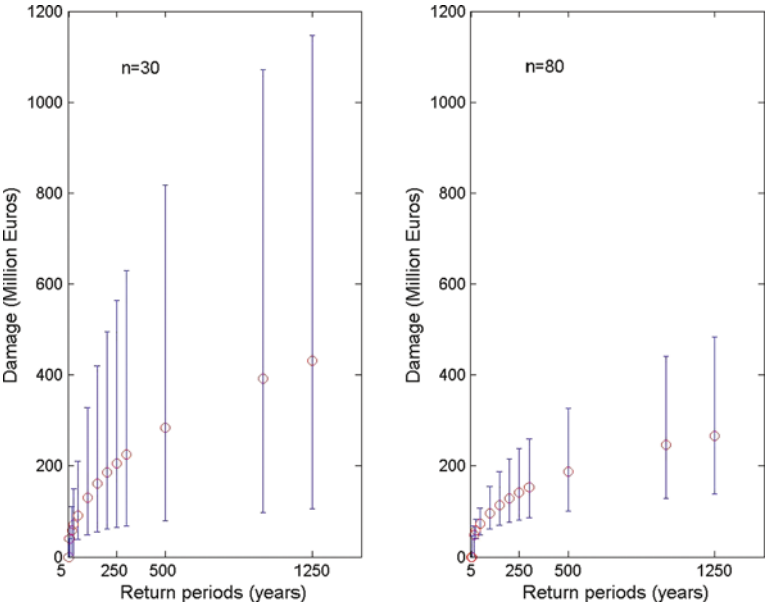


Figure 11. Damage vs. return periods for 95 % confidence intervals for $n = 30$ (left) and $n = 80$ (right)

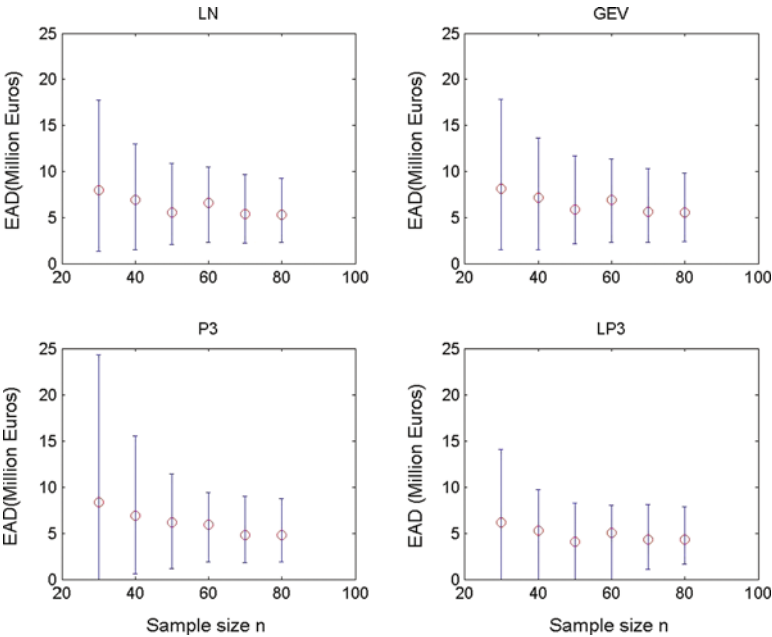


Figure 12. The effect of different distribution models and sample sizes on the EAD

size on the average amounts of EAD is smaller than the effect on the uncertainty. Thus increasing the size of data sets is an effective way to reduce the uncertainty in damage results.

4.3. Discussion

The first order method used in this paper approximates the damage model by a linear function that is locally a good approximation. The damage model here is not really linear due to the non-linearity in the QH functions and the damage model itself. Thus the first order method in fact overestimated the uncertainty in the damage results. However the results still give useful preliminary answers. Moreover, the discharge uncertainty considered here is not the only uncertainty in the damage model. There are other sources of uncertainty which may be important, for example uncertainty in channel resistance, cross-section data and damage functions. According to Xu and Booij (2004), the uncertainty caused by some hydraulic parameters and damage functions also have significant contributions to damage. The first order method can also be applied to situations where these uncertainties need to be investigated.

As mentioned in Section 2.1.1, there are several approaches available to estimate the parameters of a probability distribution. Recently the L-moment approach has been widely used because of its less sensitive to extreme events and sampling variations (Hosking (1990)). Ben-Zvi and Azmon (1997) succeeded in reducing the uncertainty involved with the choice of a probability distribution combining the L-moment approach with goodness-of-fit tests. Sankarasubramanian and Srinivasan (1999) found out that the performance of L-moments is found to improve considerably over conventional moments, especially for higher skewness. Therefore, to reduce the uncertainty in the discharge, the L-moment approach could be used.

As shown in Section 4.1, the effect of the natural variability on the T-year event discharges could be as large as 17% to 30%. In order to reduce the uncertainty, Eberle et al (2000) suggested using a stochastic rainfall generator coupled to precipitation-runoff models for the generation of long time series. This is perhaps a good alternative when more data could not be obtained. It is clear that the natural variability in this study is in fact based on historic data. The future natural variability (climate change, land use change) may even have larger effects on the river discharge (see e.g. Booij (2002)).

5. CONCLUSIONS AND RECOMMENDATIONS

This study gave some sights on the amount of uncertainty propagated into discharge and expected annual damage (the decision criterion) and the relative contributions of uncertainty caused by the choice of different distributions and the sample size. The results of this study show that the effect of the uncertainty in the river discharge (17%–30%) is aggravated when it is propagated into the damage results. The uncertainty in the damage results could be more than 100% for small sample sizes. It is also shown that both probability distribution models and sample size have

important effects on the calculation of expected annual damage. It is believed that the sample size has a larger effect on the damage results than the probability distribution models except for the LP3 model. Possibly, this could be improved by further goodness-of-fit tests.

Solutions to the considerable uncertainty in expected annual damage are by reducing the uncertainty in river discharge through obtaining more observation data, or using a stochastic rainfall model coupled to a precipitation-runoff model for the generation of long time series.

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CHAPTER 17

A STOCHASTIC MODEL FOR SIMULATING LONG TIME SERIES OF RIVER-MOUTH DISCHARGE AND SEDIMENT LOAD

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Abstract: River dynamics play an important role in the formation of deltaic and fluvial deposits. Typical scenarios comprise long periods of low discharge and sedimentation rates, alternating with flooding events that are characterised by very high erosion and deposition rates. A general problem in reconstructing the scenarios that led to the formation of fluvio-deltaic deposits is the lack of liquid and solid discharge data covering long time intervals. The objective of this study is to present a statistical method that allows the simulation of long time series of fluvial discharge from comparatively short historic records. The method captures temporal variability of river discharge by a stochastic two-parameter model. Model parameters are obtained by statistical analysis of discharge data from modern catchments, based on the hypothesis that long-term average discharge is lognormally distributed. The Discharge Model for Basins (DMB) extends this method to ancient fluvial systems by estimation of climate and catchment parameters. The method is illustrated with data sets of the Terek and Volga Rivers (Russian Federation). The Kura River (Azerbaijan) is presented as a test case in which parameters are estimated from a hydrological database of major European rivers. Tests show that the model is capable of producing estimated monthly and yearly discharge sequences comparable to measured time series, which comprise flooding events. DMB simulations of liquid and solid river-mouth discharge can be used as input for stratigraphic simulation models

Keywords: liquid discharge, sediment load, rivers, drainage basins, frequency distribution, stochastic model, Markov process, time series

1. INTRODUCTION

Order-of-magnitude seasonal and inter-annual changes in river discharge are common (Knox 1984). They exert a fundamental control on spatial deposition patterns in fluvial-dominated deltas, analogous to the alternations between storms

and fair-weather conditions that control the morphology and stratigraphy of wave-dominated coasts (Storms 2003). When the supply of water to a particular section of a river exceeds the capacity of the channel, the river floods and overbank deposition occurs. The origin and evolution of many subaerial fluvio-deltaic geomorphic features such as levees, crevasse sprays, overbank deposits, as well as avulsions and channel bifurcations are intimately linked to river floods (Bryant et al. 1993; Mackey and Bridge 1995; Slingerland and Smith 1998). Knowledge of the nature and timing of discharge and sediment loads is therefore essential to our understanding of fluvio-deltaic stratigraphy.

The selection of a model suitable for a particular problem depends mainly on the available data, and on the required detail and scale. Existing discharge models vary considerably to accommodate the wide range of problems in which discharge and sediment yield estimates are needed. The simplest models are generally used for erosion-control planning on the basis of mean sediment yield. More complex models estimate discharge and sediment yield corresponding to individual storms (Onstad 1984; Fleming and Frosi 2002). Such models are typically applied to short (historic) time scales. Indeed, reviews of different hydrological models show that only a few are applicable to geological time scales (Ward and Robinson 1990; Bedient and Huber 2002; Syvitski 2003). Long-term models fall into one of two categories: methods to estimate continental denudation, and methods to estimate the mass of sediment delivered to continental margins by rivers (Milliman and Meade 1983). Reconstruction of deltaic systems requires knowledge of discharge at the apex of a system. This disqualifies denudation models, because storage of sediment on alluvial plains makes these models unnecessarily complex. An alternative subdivision can be made between deterministic and stochastic models. Deterministic models simulate physical processes that operate in the catchment to transform precipitation into discharge, whereas stochastic models take into consideration the probability of occurrence of specific hydrological conditions (Ward and Robinson 1990). Some stochastic models only supply average values and do not take floods into account (Milliman and Meade 1983). Other models take variability into account but do not represent the Hurst phenomenon correctly (Ward and Robinson 1990). Deterministic models such as HYDROTREND (Syvitski et al. 1998), SHETRAN (Birkinshaw and Ewer 2000) and RHINEFLOW (Kwadijk and Rotmans 1995) need numerous input parameters, which rely on detailed knowledge of the river catchment. Such knowledge is generally not available in geological applications, since discharge records older than 170 years B.P. do not exist for deltaic systems (Fleming and Frosi 2002). However, some information on catchment properties and climate regimes of ancient rivers, e.g. temperature vs elevation and basin elevation, may be available (Morehead et al. 2003; Syvitski 2003). We propose to combine this type of information with modern-day discharge time series of comparable fluvial systems to construct synthetic discharge sequences, so as to offer a solution for the lack of data on liquid and solid discharge of ancient rivers.

The model presented in this paper, the Discharge Model for Basins (DMB), is based on a Markov process and provides synthetic time series, based on the assumption of lognormally distributed discharge. The aim of our model is to simulate the natural variability of monthly to yearly river discharge over geological time, 10^3 – 10^5 years, based on minimal information. Our model should simulate magnitudes and frequencies of floods, and represent periods of normal discharge as well. In other words, synthetic time series should reproduce the measurements of average discharge statistics and their variability. Several numerical experiments will be performed to test the method using data from rivers debouching in the western part of the Caspian Sea. The annual discharge of the Volga River over a period of 163 years (1937–1999) will be simulated and compared to measurements. In addition, simulations of monthly discharge of the Terek River, western Caspian shore, Russian Federation, will be presented based on a data set measured near the river mouth over a period of 14 years (1973–1991). The discharge of the Kura River, western Caspian shore, Republic of Azerbaijan, will be simulated using a minimum of assumptions, and compared to available measurements. We will conclude with several other applications of the model, which illustrate its use in assessment of flooding risk and forecasting of climate-change effects.

2. THEORY

Problems of forecasting and hindcasting data that include low-frequency and high-magnitude events are encountered in many scientific fields besides geology, e.g. econometry. Theories of mathematical statistics may be used to provide a solution to this problem if long time series are absent. The approach outlined in the following section is based on the Black and Scholes model developed in econometry that describes the behaviour of stock prices (Black and Scholes [1973]). We present a derivation for a continuous stochastic process applicable to river discharges, based on a Markov process. The derivation is adapted from Hull ([1997]), who gives a detailed mathematical description of Markov processes, and whose notation is largely followed in this paper. It should be pointed out that the Markovian property of discharge is an initial assumption given without proof.

A Wiener process is a particular Markov process where the behaviour of a variable, z , can be understood by considering the changes in its value, Δz over a time interval Δt by the equation:

$$(1) \quad \Delta z = \varepsilon \sqrt{\Delta t}$$

where ε is a random standard normal deviate. We now introduce the basic Wiener process that has zero drift rate and unit variance rate. A zero drift rate means that the expected value of z at any future time is equal to the current value. The unit variance rate means that the variance of the change in z in a time interval of length

t equals t. A generalised Wiener process for variable x can be defined in terms of dz as follows:

$$(2) \quad dx = a dt + b dz$$

where a and b are constants. It is tempting to suggest that discharge follows a generalised Wiener process, i.e. it has a constant expected drift rate and a constant variance rate. However, such a simplified assumption cannot be justified in the light of fluvial dynamics over geological time spans. We therefore introduce Ito's Lemma to describe the stochastic process followed by the variable itself. This is a generalised Wiener process where the parameters a and b are functions of the underlying variables x and t . Algebraically, an Ito process can be written as:

$$(3) \quad dx = a(x, t)dt + b(x, t)dz$$

Both the expected drift rate and the variance rate of an Ito process are liable to change over time. A reasonable assumption is that the variance of the relative change in a period of time, Δt , is independent of the discharge Q . Defining σ^2 as the variance rate of the proportional change in the discharge, then $\sigma^2 \Delta t$ is the variance of the proportional change in discharge over time Δt and $\sigma^2 Q^2 \Delta t$ is the variance of the actual change in the discharge, Q , during Δt . The instantaneous variance rate of Q is therefore $\sigma^2 Q^2$. Hence, Q can be represented by an Ito process with instantaneous expected drift rate μQ and instantaneous variance rate $\sigma^2 Q^2$. This can be written as:

$$(4) \quad dQ = \mu Q dt + \sigma Q dz$$

The model has now two basic variables. However, these variables could in turn be modelled as functions of multiple parameters. We assume that discharge follows a lognormal distribution, based on the fact that it is a non-negative quantity, whereas its upper tail is unbound. Additional support for this assumption derives from the common use of lognormal-type distribution functions in hydrology to predict floods: the lognormal distribution, the gamma distribution and the log Pearson type 3 distribution (Bedient and Huber 2002). Ito's Lemma is used to model the discharge process by introducing the term in Q . Hull (1997) shows that the Lemma can be viewed as an extension of differential calculus. Define:

$$(5) \quad G = \ln Q$$

Since

$$(6) \quad \frac{\partial G}{\partial Q} = \frac{1}{Q}, \quad \frac{\partial^2 G}{\partial Q^2} = -\frac{1}{Q^2}, \quad \text{and} \quad \frac{\partial G}{\partial t} = 0,$$

Then, Ito's equation shows that the process followed by G is:

$$(7) \quad dG = \left(\mu - \frac{\sigma^2}{2} \right) dt + \sigma dz$$

Since σ and μ are presumed constant for now, this equation indicates that G follows a generalised Wiener process with constant drift rate $\mu - \sigma^2/2$ and constant variance rate σ^2 . This means that the time rate of change in G is normally distributed with mean

$$(8) \quad \left(\mu - \frac{\sigma^2}{2} \right) dt$$

and variance

$$(9) \quad \sigma^2 dt.$$

The value of G at time t_0 is $\ln Q_{t_0}$, its value at time t_i is $\ln Q_{t_i}$, where Q_{t_i} is the discharge at time t_i . Its change during the time interval $t_i - t_0$ is therefore $\ln Q_{t_i} - \ln Q_{t_0}$. Hence:

$$(10) \quad \ln Q_{t_i} - \ln Q_{t_0} \sim \phi \left[\left(\mu - \frac{\sigma^2}{2} \right) (t_i - t_0), \sigma \sqrt{t_i - t_0} \right],$$

The discharge equation still involves two variables, σ and μ . The parameter μ is the expected change in the discharge. μ is the dimensionless direction coefficient of a trend function for every discrete time step. In this study we will restrict ourselves to a constant trend based on the historical average discharge. Therefore, μ will be assumed zero. The parameter σ , discharge volatility, describes the variability of discharge, which is estimated from historical data and extrapolated to longer time scales if necessary. The following method is used to estimate σ from historical data. Define the number of observations as n ; the discharge of the i -th interval ($i = 0, 1 \dots n$) as Q_i , and the length of the time interval in years as τ . Let

$$(11) \quad u_i = \ln \left(\frac{Q_i}{Q_{i-1}} \right) \text{ for } i = 1, 2 \dots n.$$

Since

$$(12) \quad Q_i = Q_{i-1} e^{u_i},$$

u_i is the continuously compounded return in the i -th interval. The estimate of the standard deviation, s , of u_i is given by:

$$(13) \quad s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (u_i - \bar{u})^2}$$

where $\bar{u}$ is the mean of the calculated u_i 's of Equation (11).

The standard deviation of u_i is $\sigma\sqrt{\tau}$. The variable s is an estimate of $\sigma\sqrt{\tau}$. Therefore it follows that σ can be estimated as s^* , where:

$$(14) \quad s^* = \frac{s}{\sqrt{\tau}}$$

Suppose that time is measured in years, and that the variables were also determined per year. It follows that the value of variable σ is $\sigma\sqrt{1}$ (equation 14). As long as the time steps between measurements and simulation are equal, the derived value for s can be directly used as an estimate of σ . According to statistical theory, the best estimate of σ is obtained by letting n be as large as possible. However, σ is likely to change abruptly in long time series, as a result of human intervention (e.g. construction of dams) or natural phenomena (climate change). Care should be taken not to mix different σ regimes when using data from long time intervals.

Parameter μ has been proposed to be zero and for σ it has been shown that it can be estimated from historical data. The next step is where equation 10 evolves into the following probability function:

$$(15) \quad \ln Q_{t_i} - \ln Q_{t_0} \sim \phi \left[\left(-\frac{\sigma^2}{2} \right) (t_i - t_0), \sigma \sqrt{t_i - t_0} \right]$$

which can be rewritten as:

$$(16) \quad \ln Q_{t_i} \sim \phi \left[\ln Q_{t_0} + \left(-\frac{\sigma^2}{2} \right) (t_i - t_0), \sigma \sqrt{t_i - t_0} \right]$$

From the properties of the lognormal distribution it can be shown that the expected value of Q for time t_i is given by

$$(17) \quad E(Q_{t_i}) = Q_{t_i} e^{\mu(t_i - t)}$$

if $\mu = 0$ then

$$(18) \quad E(Q_{t_i}) = Q_{t_i}$$

If the discharge is lognormally distributed and μ is zero then the expected value is also equal to the average discharge ($\bar{Q}$)

$$(19) \quad E(Q_{t_i}) = \bar{Q}$$

In equation 19 it is stated that the expected value for every t_i (1, 2, 3, ..., n), Q_{t_i} , is equal to the average discharge and therefore time independent. However this does not imply that σ is also time independent according to equation 16, the domain of the possible outcomes will grow with $\sqrt{dt}$, where dt is equal to the accumulated time steps, defined as t_n . Nevertheless, it can be reasoned that σ remains constant for every t_n , to better constrain the simulation results. A constant value for σ is only possible when dt is constant. Therefore it is considered that successive simulated values are independent, which seems reasonable given the typical time intervals considered in this study (years and months). Assuming that each result is independent of the former, similar to throwing dice, one can see a synthetic sequence as the possible outcomes for a single time step. As a result, dt can be

assumed equal to 1, and σ will remain constant. This is in contrast with the initial assumption of a Markov process in which the value at every next time step is only based on its present value (Hull 1997).

Suppose that the variables were determined per year and are time independent. This results in the following probability distribution for Q_T .

$$(20) \quad \ln Q_{t_i} \sim \phi \left[\ln \bar{Q} + \left(-\frac{\sigma^2}{2} \right), \sigma \right]$$

Creating a synthetic discharge sequences is now possible by sampling repeatedly from equation (20) resulting in:

$$(21) \quad \ln Q_{t_i} = \ln \bar{Q} + \left(-\frac{\sigma^2}{2} \right) + \sigma \varepsilon$$

where ε is the random standard normal deviate described in equation (1). Also note that the values of Q_{t_i} are dependent on the average discharge, a historical value, therefore formally disqualifying the derived equations (20) and (21) as a Markov process.

3. SIMULATIONS FROM DISCHARGE MEASUREMENTS

As short-lived floods account for most of the annual discharge, and flood magnitude is related to higher-than-normal mean discharge, the annual discharge of a river is strongly related to the annual average discharge (Syvitski and Morehead 1999; Coppus and Imeson 2002). It is therefore possible to use the inter-annual variability as a measure for short-lived events. The model is used to apply this principle to data from the Volga River, Russian Federation. The river drains $1.36 \times 10^6 \text{ km}^2$ of the southwest side of the Ural Mountains and a large section of the European part of the Russian Federation. The catchment is relatively flat and is mainly used for the cultivation of crops. The area has a typical continental climate with cold and dry winters. The average daily temperature in January is -10°C , with an average monthly precipitation of 25–50 mm. Each winter, the Volga River freezes for a period of up to 120 days. The summers are wetter and warmer with an average daily temperature in July of 20°C and an average monthly precipitation of 150–200 mm. The Volga has over 2600 tributaries. The river enters the Caspian Sea and is its main source of water. The river mouth lies currently 28 meters below global sea level. The Volga is the 17th largest river in the world in terms of discharge, and the 15th in terms of catchment area (Foley 2003). A gauge near the apex of the delta has been used to collect discharge data since 1837. Measurements show that the discharge of The Volga River is characterised by a high interannual variability. The highest discharge was registered in 1867 at $14604 \text{ m}^3 \text{ s}^{-1}$ ($454 \text{ km}^3 \text{ yr}^{-1}$), and the lowest $4142 \text{ m}^3 \text{ s}^{-1}$, ($129 \text{ km}^3 \text{ yr}^{-1}$) in 1842. The average discharge is $8076 \text{ m}^3 \text{ s}^{-1}$ ($251 \text{ km}^3 \text{ yr}^{-1}$) (Kroonenberg et al 1997). Dam constructions, which dampened

the inter-annual discharge variability started after 1919. The largest construction is situated near Volgograd.

Annual average discharge data from the period 1837–1999 were analysed and used to produce synthetic discharge time series. Analysis of the data gave an average discharge of $8076 \text{ m}^3 \text{ s}^{-1}$ and an σ of 0.22. Using these values, 250 annual discharge series of 163 years length were generated. The results of the simulations are plotted as a histogram together with the measured data in Figure 1. More than 90% of the measured data fall within one standard deviation of the simulated data, showing that the model produces realistic synthetic time series with appropriate magnitude-frequency distributions.

A time step of a year is often employed in geological modelling, but as a result of ongoing technological developments the use of smaller time steps has become a realistic possibility. A slightly different approach was developed to deal with monthly time steps. Due to the seasonality of river systems and our desire to faithfully reproduce the high-magnitude events it is necessary to break down the time series into a number of sequences, so as to avoid the loss of seasonal variation through averaging. The breakdown is also essential because the frequency-magnitude histogram of monthly discharge is often not lognormally distributed in the presence of a seasonality signal.

A synthetic monthly discharge record was simulated from a time series of the Terek River, western Caspian shore, Russian Federation (1973–1991). The Terek River originates in northern Georgia and flows north and then east through Russia to the Caspian Sea. It is the main river draining northward from the Greater

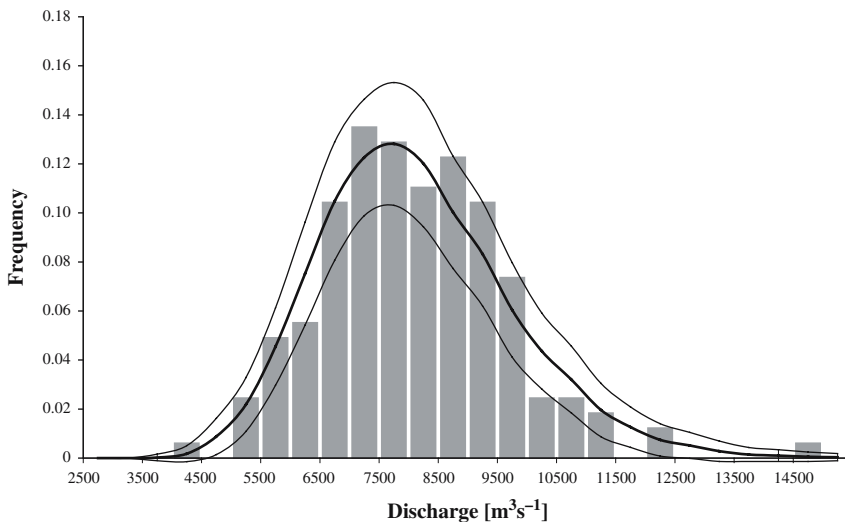


Figure 1. Annual average discharge of the Volga River (1837–1999) plotted as histogram. Average of 250 simulations plotted as black line. Area enclosed by dashed lines represents simulations within one standard deviation of the average

Caucasus. The Terek is approximately 600 km long and drains a basin of 43700 km² (Aybulatov, 2001). Figure 2 clearly shows the seasonality in the average monthly discharge. A seasonal disaggregation into high and low seasons was carried out before analysis. The low-discharge season lasts typically from September to April (average $Q < 200 \text{ m}^3 \text{ s}^{-1}$) and the high-discharge season comprises the remaining four months, May to August (average $Q > 200 \text{ m}^3 \text{ s}^{-1}$). Peak discharges in some years were later than May. It was decided to include all periods with monthly discharges exceeding $200 \text{ m}^3 \text{ s}^{-1}$ in the high season.

The estimated average discharge in the low season equals $98 \text{ m}^3 \text{ s}^{-1}$ with an σ of 1.09; the average discharge in the high season equals $721 \text{ m}^3 \text{ s}^{-1}$ with an σ of 0.72. The discharge-frequency distribution for the low season complies with the assumption that the discharge is lognormally distributed. Figure 3 shows that more than 90% of the measured data falls within one standard deviation of the simulated data. In contrast, Figure 4 shows that the measured discharge-frequency distribution of the high season is not well approximated by a lognormal distribution. The reason for this discrepancy could be that the number of observations is insufficient to construct a representative frequency-magnitude distribution, since the high-discharge season is shorter than the low-discharge season. Hence, the parameters, σ and the average discharge, are an estimation of the long-term magnitude-frequency distribution. The minimum sample size for a stable estimate appears to around $n=150$, as may be inferred from the analyses of the Volga and low-season Terek data sets.

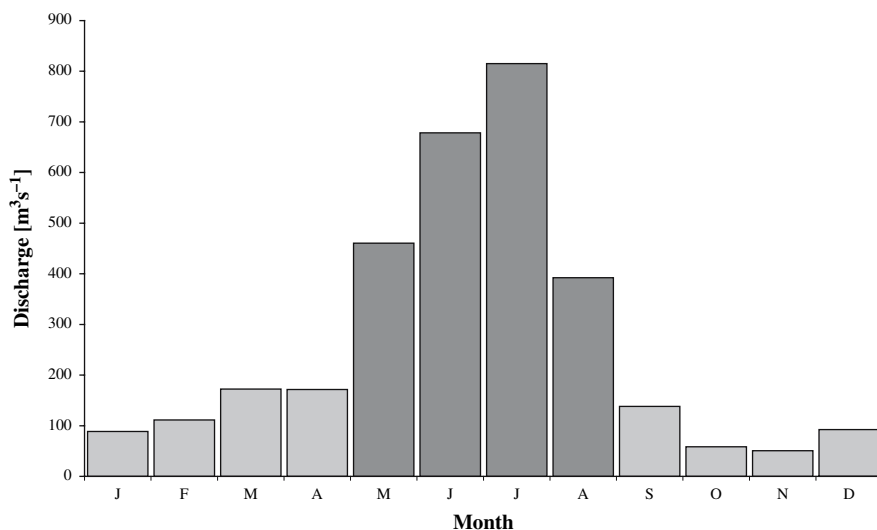


Figure 2. Monthly average discharge of the Terek River (1973–1991). Low-discharge season (average $Q < 200 \text{ m}^3 \text{ s}^{-1}$) lasts from September to April; high-discharge season (average $Q > 200 \text{ m}^3 \text{ s}^{-1}$) lasts from May to August

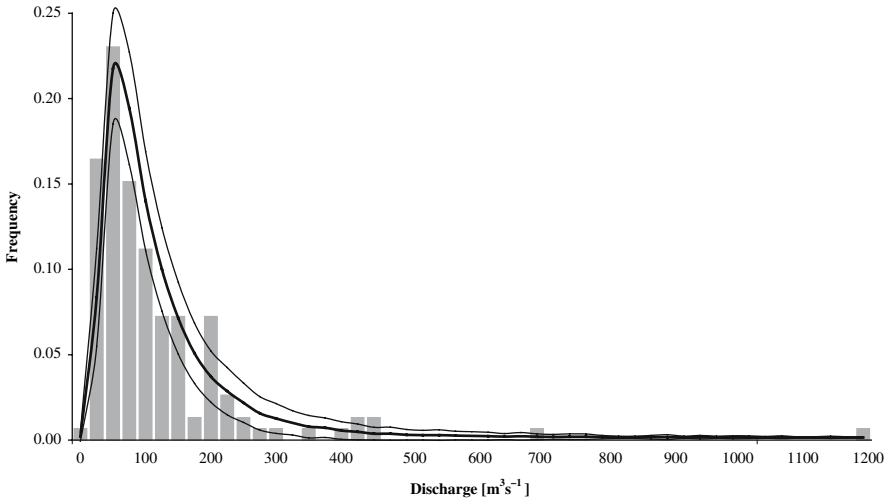


Figure 3. Measured monthly average discharge (low season: September- April) of the Terek River between 1973 and 1991 plotted as histogram. Average of 250 simulations plotted as black line. Area enclosed by dashed lines represents simulations within one standard deviation of the average

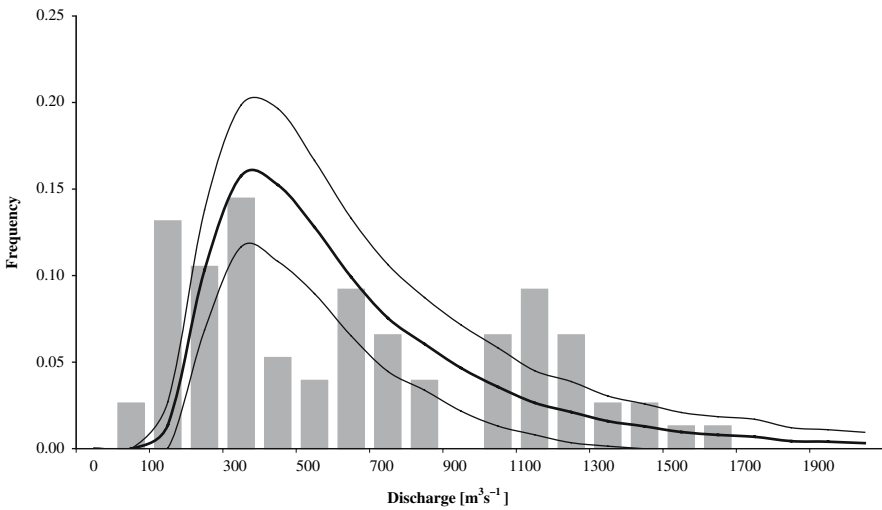


Figure 4. Measured monthly average discharge (high season: May- August) of the Terek River between 1973 and 1991 plotted as histogram. Average of 250 simulations plotted as black line. Area enclosed by dashed lines represents simulations within one standard deviation of the average

4. PREDICTION OF RIVER DISCHARGE

The Discharge Model for Basins (DMB) is based on the above theory, but extends its scope to simulation of river-mouth discharge on geological time scales. Because geological time scales exceed measured time series, assumptions need to be made with regards to average discharge and σ . We propose to estimate these parameters from climate and catchment properties of the river to be simulated. As a first step towards this goal, climatic and physiographic data are used to classify and analyse modern catchments. The data were obtained from the NOAA (National Oceanic and Atmospheric Administration) and SAGE (center for Sustainability And the Global Environment) internet sites (Foley 2003).

We will start by estimating the first model parameter, the average discharge. The most basic estimate of discharge can be described as a function of catchment area and the precipitation that falls within this area. However, the spatio-temporal distribution of discharge may differ considerably between basins with different climate and physiography, as will the storage capacity and evaporation. As these differences should be acknowledged, our scheme for estimating the average discharge is based on a classification of catchments according to Milliman and Syvitski (1992), which takes into account many of these properties (Table I). Twenty-eight rivers from Europe were classified according to this system to illustrate our method (Table II). They cover four groups, i.e., lowland, upland, alpine Europe and non-alpine Europe. We constructed regression functions to estimate discharge from catchment area for each class of rivers, using the relation:

(22) $Q = \alpha \ln(A) + b$

Where A is the drainage basin in km^2 and Q is average discharge in $\text{m}^3 \text{s}^{-1}$. Coefficients α and b are based on analyses for each class of rivers (Table III). The trend lines are shown together with the input data in Figure 5. estimated discharge values are listed in the last column of Table II.

The second model parameter, volatility, is also thought to be climate and catchment dependent. Morehead et al (2003) provide a function from which the discharge volatility may be derived by rewriting it as:

(23) $\sigma = a(0.99995^{\bar{Q}})$

Table 1. River classification based on Milliman and Syvitski (1992)

Drainage basin class	Maximum elevation of the hinterland
High Mountain	> 3000 m.
South Asia/Oceania	1000–3000 m.
N/S America, Africa & Alpine Europe	1000–3000 m.
Non-Alpine Europe & High Arctic	1000–3000 m.
Upland	500–1000 m.
Lowland	100–500 m.
Coastal Plain	< 100 m.

Table 2. Catchment and annual discharge data (Foley 2003), combined with catchment classification and estimated average annual discharge

River	Catchment (km ²)	Average annual discharge (m ³ sec ⁻¹)	Classification	Estimated average annual discharge (m ³ sec ⁻¹)
Trent	7,486	90	lowland	59
Thames	9,948	81	lowland	108
Weser	37,790	316	lowland	338
Ems	8,345	86	lowland	78
Maas	29,000	326	lowland	292
Seine	44,320	270	lowland	366
Neman	81,200	539	lowland	470
Elbe	123,532	744	upland	618
Odra	109,729	536	upland	593
Kymi	36,535	302	upland	360
Vuoksi	61,275	590	upland	470
Kemi	50,790	535	upland	430
Jucar	17,876	129	upland	209
Douro	91,491	544	upland	555
Wisla	194,376	1056	non-alpine Europe	961
Glomma	40,221	672	non-alpine Europe	583
Guadalquivir	46,995	568	non-alpine Europe	621
Loire	110,000	835	non-alpine Europe	824
Garonne	52,000	609	non-alpine Europe	645
Vannern- Gota	46,830	531	non-alpine Europe	620
Lule	24,490	466	non-alpine Europe	464
Tiber	16,545	231	non-alpine Europe	370
Tay	4,587	180	non-alpine Europe	63
Danube	807,000	6498	Alpine Europe	6571
Po	70,091	1514	Alpine Europe	1071
Rhone	95,590	1694	Alpine Europe	1769
Rhein	159,680	2291	Alpine Europe	2924
Ebro	84,230	1260	Alpine Europe	1484

Equation 23 supports the observation that the volatility is proportional inversely to the size of the catchment. Parameter a depends on climate, specifically temperature (Table 4). Application of this equation to a data set of rivers from different climates gives acceptable results (Table 5). In warm regions (Mediterranean climate zone) a high value for σ is measured while in the more temperate climates a lower σ

Table 3. Coefficient of $Q = \alpha \ln(A) + b$

Class	A	b
Alpine Europe	2251.0	-24045
Non-alpine Europe	239.5	-2249
Upland	211.7	-1863
Lowland	172.5	-1480

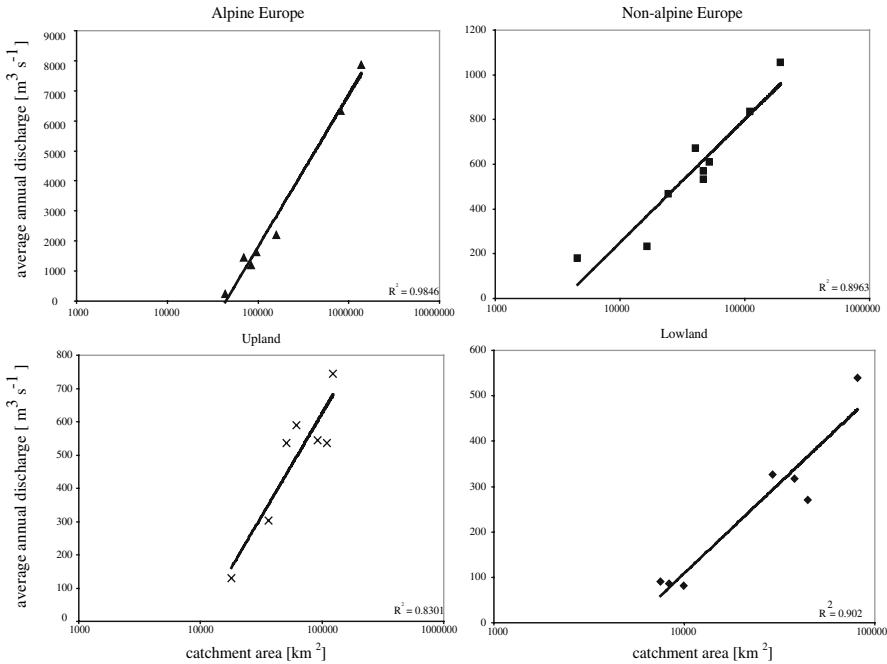


Figure 5. Catchment and discharge data of Table 2 plotted for each class of rivers. Triangles = alpine Europe; crosses = upland; squares = non-alpine Europe; diamonds = lowland catchments. Coefficients of regression lines listed in Table 3

value is common. The above equations allow us to generate long time series of fluvial discharge from minimal assumptions about drainage-basin characteristics. It should be noted that the limited number of rivers used to estimate the coefficients in Equations 22 and 23 does not justify extrapolation to other fluvial systems without reservation. We believe that the data presented are sufficient to illustrate the methodological aspects of our approach, but acknowledge the fact that parameter estimates are likely to improve by using more data.

Table 4. Climate subdivision based on monthly average temperature ($^{\circ}\text{C}$)

Climate zone	Temperature		a
	Coldest month	Hottest month	
Cold	$< -3^{\circ}$	$< 10^{\circ}$	0.20
Temperate (Continental)	$< -3^{\circ}$	$> 10^{\circ}$	0.30
Temperate (Maritime)	$> -3^{\circ}$	$> 10^{\circ}$	0.40
Mediterranean	$> -3^{\circ}$	$> 18^{\circ}$	0.65

Table 5. Climate interpretation and discharge data with the resulting estimated parameters and measured parameter

River	Climate zone	Average discharge ($\text{m}^3 \text{sec}^{-1}$)	a (–)	estimated σ (–)	measured σ (–)
Glomma	Cold	673	0.20	0.19	0.21
Odra	Temperate (Continental)	536	0.30	0.29	0.27
Elbe	Temperate (Continental)	744	0.30	0.29	0.26
Wisla	Temperate (Continental)	1,056	0.30	0.28	0.29
Ebro	Temperate (Continental)	1,260	0.30	0.28	0.28
Rhein	Temperate (Continental)	2,292	0.30	0.27	0.30
Danube	Temperate (Continental)	6,499	0.30	0.22	0.23
Garonne	Temperate	609	0.35	0.34	0.36
Po	Temperate	1,515	0.35	0.32	0.36
Rhone	Temperate	1,695	0.35	0.32	0.32
Maas	Temperate (Maritime)	326	0.40	0.39	0.39
Seine	Temperate (Maritime)	270	0.40	0.39	0.48
Loire	Temperate (Maritime)	835	0.40	0.38	0.42
Guadalquivir	Mediterranean	568	0.65	0.63	0.67
Douro	Mediterranean	544	0.65	0.63	0.65

5. KURA RIVER SIMULATION

The Kura River is the largest watercourse in the South Caucasus. It originates at 2720 meters above sea level on the northeast slopes of Kizil-Giadik (Turkey). It flows through Georgia and Azerbaijan to debouch into the Caspian Sea (South Caspian Basin). In the Kura Basin, the Kura River merges with its major tributary, the Araks River. The Araks River drains the eastern Lesser Caucasus. The total length of the Kura River is 1515 km and the total area of the catchment is 188000 km² (including the Araks catchment). The drainage basin occupies the greater part of the Lesser Caucasus and the southeastern Greater Caucasus.

The total annual inflow from Georgia through the Kura River is estimated at 11.9 km³. The total annual inflow of the main Araks River is estimated at 6.7 km³. The total annual inflow of the tributaries of the Kura and Araks rivers coming from Armenia and the south flank of the Greater Caucasus is estimated at 2.3 km³. The total inflow into Azerbaijan is thus estimated at 21.0 km³ yr⁻¹ (Bousquet and Frencken [1997]). The river-mouth discharge averaged 17.1 km³ yr⁻¹ (551 m³ s⁻¹) between 1938 and 1984. The difference in water balance is largely attributable to irrigation. Intake of water for irrigation significantly reduced the average annual river-mouth discharge from at least 1961 onwards. Average river-mouth discharge decreased to 414 m³ s⁻¹ between 1991 and 2000 (Warren and Kukosh [2003]).

Highest and lowest average annual discharges recorded between 1938 and 1984 are 816 m³ s⁻¹ in 1963 and 277 m³ s⁻¹ in 1962, respectively. Monthly average discharge ranged from 120 m³ s⁻¹ in August to 2250 m³ s⁻¹ in May (Salmanov [1997]). In 1953, the Mingechaur Reservoir was constructed in the North-west of Azerbaijan. Measurements show a 7% decrease of water discharge from

$554 \text{ m}^3 \text{ s}^{-1}$ (1938–1952) to $515 \text{ m}^3 \text{ s}^{-1}$ (1953–1965). As a result of dam construction, the annual peak flood has been displaced from June to May, and it has become less pronounced. The low discharge period during winter is also less pronounced (Belyayev [1971]). These changes in discharge regime cannot be directly coupled with dam construction because of: 1) the short period of averaging, 2) the influence of the Araks River that joins the Kura River downstream of the reservoir, 3) increase in the use of Kura River water for irrigation, and 4) a possible increase of water evaporation on the alluvial plain (global warming).

We simulated the Kura River discharge by using drainage-basin area as input, and by assuming that the Kura drains a non-alpine mountainous area in a temperate land climate. Application of Equations 22 and 23 resulted in an annual average discharge estimate of $659 \text{ m}^3 \text{ s}^{-1}$ and a volatility estimate of 0.29. Comparison with measured data reveals that the average annual discharge is slightly underestimated but the volatility is correct. Figure 6 shows the results of our simulations, together with the difference between measured and simulated discharge. The offset between measured and simulated data is attributable to the limitations of our simple model and modest database. However, the magnitude-frequency relation in the high discharge regime ($Q > 700 \text{ m}^3 \text{ s}^{-1}$), which is by far the most relevant to prediction of erosional and depositional events, is adequately reproduced.

Analysis of the high-discharge regime (upper tail of the discharge distribution) allows flooding risk to be predicted. Statistical methods based on previous flooding experience have been used since the 1920's for flood estimation (Bedient and

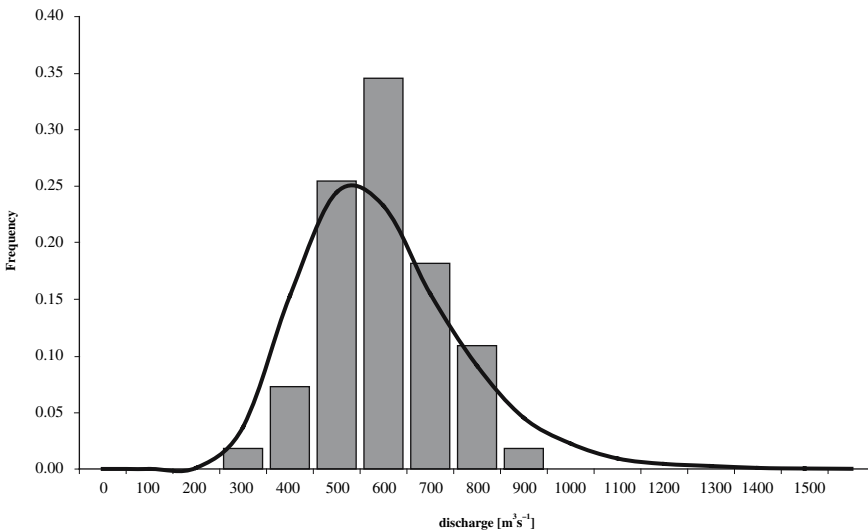


Figure 6. Frequency distribution of the average monthly discharge of the Kura River (1930–1984) represented by columns compared with the simulated discharge data (black line) for similar period

Table 6. Estimated flood magnitudes (Kura River, Azerbaijan), using $\sigma = 0.29$ and average discharge $659 \text{ m}^3 \text{ s}^{-1}$

Return period [year]	CDF	z	Q [$\text{m}^3 \text{ s}^{-1}$]
500	0.998	2.878	1455.8
200	0.995	2.576	1333.7
100	0.99	2.326	1240.4
50	0.98	2.054	1146.3
25	0.96	1.751	1049.9
10	0.9	1.282	916.4
5	0.8	0.842	806.6
2	0.5	0	631.9

Huber (2002). These methods rely on long, high-quality discharge records. Since such methods assume that floods are independent, only the maximum floods of each year are needed to form an independent series of annual peaks (Fleming and Frost (2002)). Analysis of time series generated with DMB allows the re-occurrence periods of floods to be estimated in catchments for which insufficient data are available to construct a frequency distribution of observations. To illustrate this method, we have used the simulated Kura River discharge record to predict the occurrence of Kura river floods of a given magnitude (Table 6).

6. CLIMATE CHANGE AND SEDIMENT SUPPLY

The next step is to apply the method to simulation of long time series corresponding to climate-change scenarios, which are the rule rather than the exception on geological time scales. In this exercise we shall extend the application of DMB to estimation of fluvial sediment loads, by using a regression function (Syvitski et al., (2003)) that predicts sediment load as a function of discharge, relief and temperature:

(24)
$$Qs = \alpha_2 Q^{\alpha_3} H^{\alpha_4} e^{kT}$$

where Qs is sediment load (kg s^{-1}), Q is average discharge ($\text{m}^3 \text{ s}^{-1}$), H is maximum relief (m) and T is basin-averaged temperature ($^{\circ}\text{C}$).

As shown above, relief and area are the most important parameters for estimating the average discharge of a drainage basin. We will assume that they remain essentially constant during the simulated time interval. Simulation of the discharge of a given drainage basin under different climate conditions merely requires a change in the volatility value. In the present experiment the average discharge was set to $550 \text{ m}^3 \text{ s}^{-1}$, the value corresponding to the Kura River. Values of the parameters of Equation (24) were based on the regression coefficients provided by Syvitski et al. (2003) for a Northern hemisphere temperate climate setting, and on a value $H = 2700 \text{ m}$ representing the Kura River drainage basin. Four different temperature

Table 7. Regression coefficients for equation 24

Climate zone	σ	H (m)	T (°C)	α_2	α_3	α_4	k
Cold	0.20	2700	5	0.0011	0.53	1.1	0.06
Temperate (Continental)	0.30	2700	10	0.0011	0.53	1.1	0.06
Temperate (Maritime)	0.40	2700	15	0.0011	0.53	1.1	0.06
Mediterranean	0.65	2700	20	0.0011	0.53	1.1	0.06

and volatility values (Table 7) were used to generate liquid and solid discharge records that ought to be representative of the Kura River basin.

Figure 7 shows the effects of climate change as expressed by different values of volatility and temperature. The magnitude-frequency distributions of liquid discharge and associated sediment loads are shown in Figure 8.

Effects of climate change are clearly reflected in the distributions of both discharge and sediment load. The area under the sediment load curves, which represents a measure of the total sediment load, was calculated with a discrete integration method (Table 8). The results show that climate-controlled differences between drainage basins are largely attributable to the relative importance of extreme events.

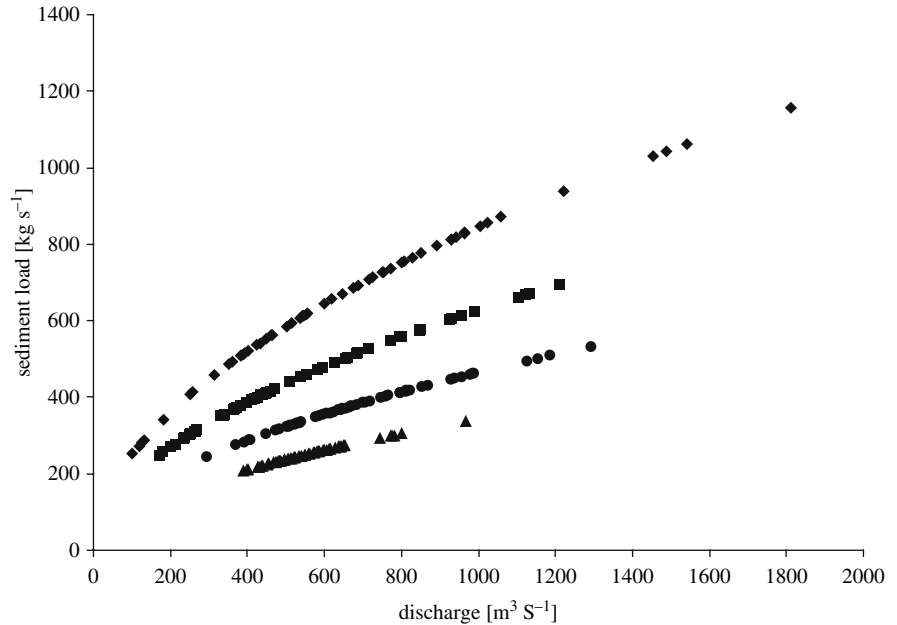


Figure 7. Fifty-five discharge events with associated sediment loads. Triangles = cold climate; spheres = temperate (continental) climate; squares = temperate (maritime) climate; diamonds = mediterranean climate. Temperature changes result in a shift of the entire curve, whereas volatility changes affect the spread of the data on each curve (parameter values in Table 7)

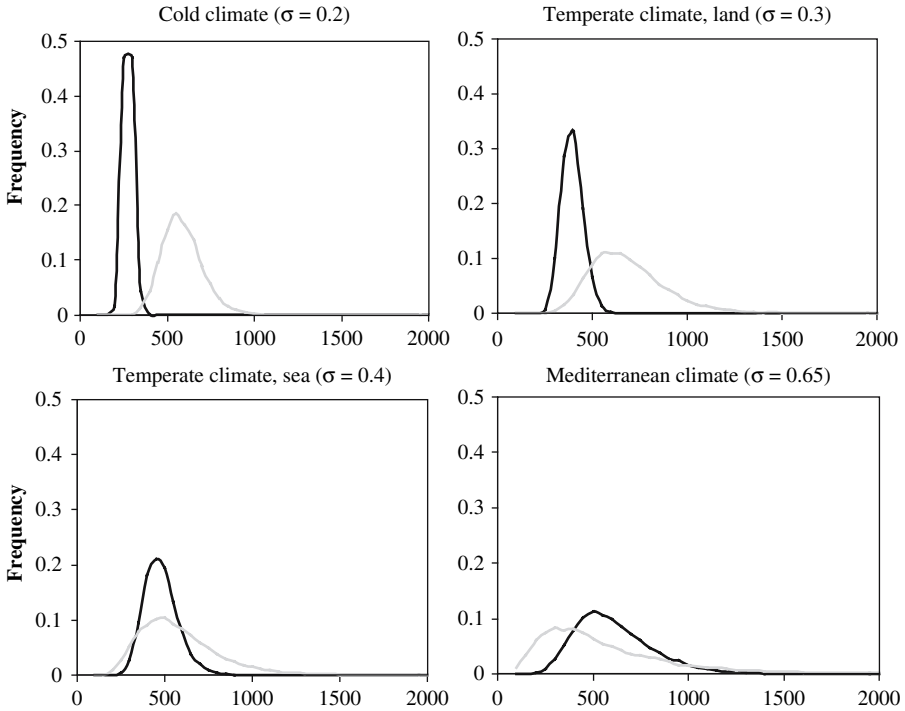


Figure 8. Frequency distributions of simulated liquid and solid discharge events over period of 10 kyr for different climate settings. Increase in volatility is associated with a warmer climate (range from 0.2 to 0.65; Table 4). The grey line represents the discharge in $\text{m}^3 \text{s}^{-1}$. The black line represents the sediment load in kg s^{-1}

In a final test, Equation 24 was used to estimate sediment-load distributions of the Kura River from a measured discharge sequence and the synthetic sequence shown in Figure 6. A significant discrepancy between measured and predicted discharge distributions was observed, attributable to the inaccurate estimation of average discharge from drainage-basin characteristics. Interestingly, Figure 9 shows that the solid load distributions calculated from both discharge records are quite similar. This result confirms the importance of discharge volatility, which controls the

Table 8. Simulated average sediment yield in different climate zones

Climate zone	σ	Sediment yield (10^6 kg)
Cold	0.20	8,744
Temperate (Continental)	0.30	12,415
Temperate (Maritime)	0.40	14,856
Mediterranean	0.65	19,338

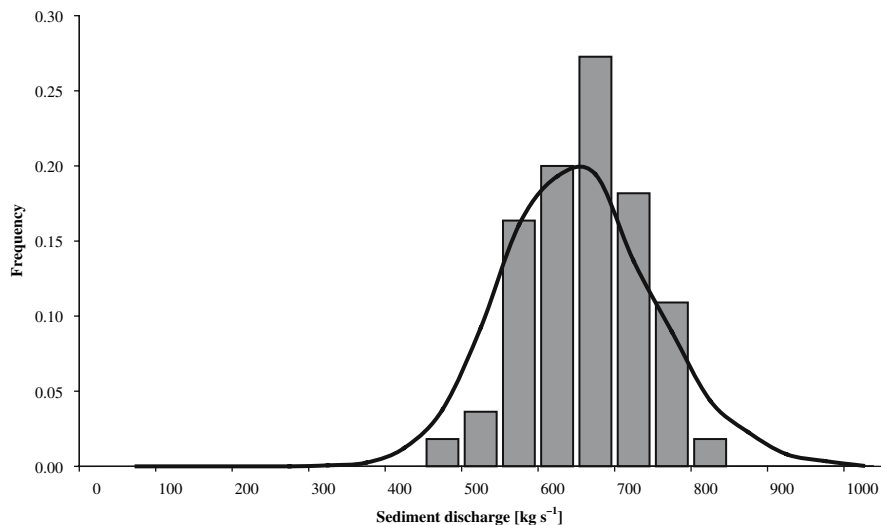


Figure 9. Frequency distribution of the simulated monthly sediment load based on measurements of the Kura River (1930–1984), represented by columns, compared with the simulated sediment load data (black line) based on a synthetic sequence shown in Figure 6

relative importance of high-discharge events, for accurate sediment load estimation over long time scales.

7. DISCUSSION AND CONCLUSIONS

The purpose of this study is to illustrate the application of a statistical technique to produce long time series of liquid and solid discharge to continental margins. Starting from the assumption of lognormal discharge, we show that discharge variability can be described as a simplified Markov process with two parameters. This method is illustrated by estimation of the two parameters, average discharge and discharge volatility, from comparatively short historical records of two rivers. Simulation of discharge records with these parameters produces acceptable results. The Discharge Model for Basins (DMB) is an extension of the statistical method to cover cases in which no detailed knowledge of the drainage basin is available. The regression coefficients used in our applications of DMB are based on a limited number of case studies only, and we recognise that they cannot be used without reservation. However, the examples presented show that the method is useful and merits extension of the database. We show that reasonably accurate time series of discharge and sediment load may be generated from a limited number of robust drainage-basin characteristics. DMB thus offers a simple and attractive method for generating input records for process-response simulation of ancient fluvial-dominated deltaic and shallow-marine sedimentary systems. Simulated frequency distributions of discharge can be used to calculate the magnitude of average discharge events for a certain return interval, which

allows risk evaluation for ungauged catchments. Another possibility is to use different climate scenarios for a given catchment, to forecast the effects of climate change on discharge and sediment load.

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SECTION IV

FLOOD FORECASTING

CHAPTER 18

FORECASTING FLASH FLOODS WITH AN OPERATIONAL MODEL

Application in the South-East of France (Gard)

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Abstract: The flash flood forecasting model ALHTAÏR (“Alarme Hydrologique Territoriale Automatisée par Indicateur de Risque”) has been developed during the last five years by the flood-warning service of the Gard Region (SAC-30), in the South-East of France. A spatial version for the flash flood forecasting model is described in this paper. This flash flood forecasting model is divided in three separate tools, which allow a flood hydrograph simulation for each location, covering all the rivers of the Gard Region, in a real time processing: CALAMAR[®] simulates the rainfall intensity on each square kilometre of the study area every five minutes. This georeferenced information is obtained by the interpretation of radar images. HYDROKIT[®] gives the hydrographical characteristics of a studied watershed using a DEM (Digital Elevation Model) for calculating the concentration time. ALHTAÏR software, processes the data obtained by the two previous tools and with a module of time concentration and a module of production (calculation of effective rainfall) calculating in real time the flood hydrograph. The model that calculates the effective rainfall, based on the Horton principle, takes six parameters into account. For the first version of ALHTAÏR, these parameters are the same for the whole SAC-30 supervised territory. The principal results of this version show a good flood crest synchronization but a general overestimation of the peak flow. This result was observed during the flash floods of the Gard Region in September 2002. To improve the ALHTAÏR results, a spatial approach has been tested. The results presented in the paper, show that the spatial approach according to infiltration capacity improves the reconstitution of the flood hydrograph

Keywords: flash flood, forecasting model, flood warning service, Mediterranean region

1. INTRODUCTION

The Gard Region, in the South-East of France, is located between the Mediterranean and the first foothills of Central Massif (*Les Cévennes*). This geographic position (see Figure 1) makes this Region particularly vulnerable to flash floods. Each autumn, some storm events form on the sea and pushed by south winds provoke some extreme rainfall events (Rivrain, 1997). This climatic phenomenon is called “épisode Cèvenol”. During the 8th and the 9th September 2002, an extreme “épisode Cèvenol” occurred in the Gard Region. The precipitation was very important, with the measured rainfall exceeding 650 mm over a period of 48 hours for some areas. The resulting floods had discharges higher than $20 \text{ m}^3/\text{s}/\text{km}^2$ (Gaume et al. 2003a) for small watersheds (less than 10 km^2 , principal tributaries of Gardon river, Vidourle river and Cèze river). One of explanations was the combination of the large area and the duration of the storm event. The flood caused 22 fatalities and 1.2 billion euros damage.

In the Gard Region, the flood warning service is responsible for the whole drainage network yet has hydrometric stations on the main streams. Therefore proposed to use flood modelling to improve flood forecast.

This paper describes this flash flood forecasting model and the first results for some small watersheds during the extreme floods of September 2002. The principal development of this model will be presented, namely the spatial variation of the infiltration capacity.

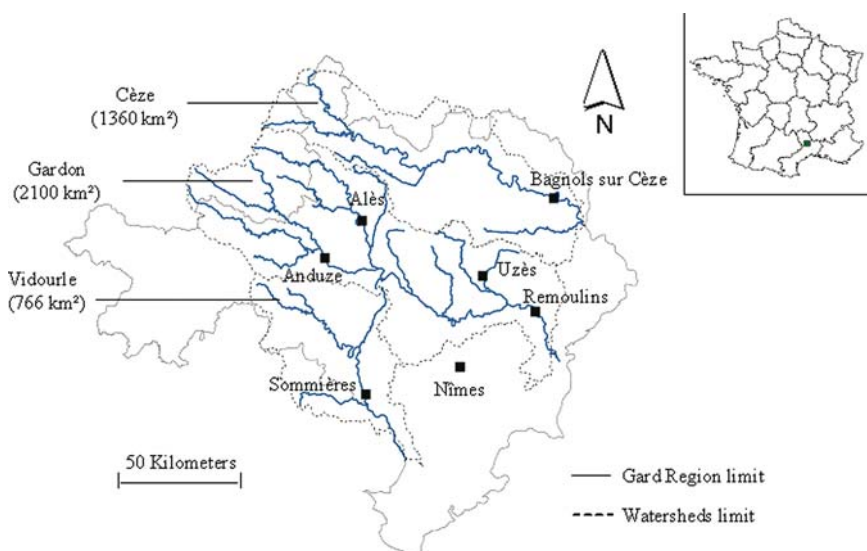


Figure 1. Gard region and the principal's rivers location

2. THE MODEL ALHTAÏR: CONTEXT AND ISSUES

The flood-warning service of the Gard Region (SAC-30) has for five years been developing the flash flood forecasting model ALHTAÏR (**AL**arme **H**ydrologique **T**erritoriale **A**utomatisée par **I**ndicateur de **R**isque) (Bressand, 2002). The purpose of this model is to produce a flood hydrograph for each rivers location, in real time, for the area under supervision of the SAC-30. The forecast model is more efficient for the catchments areas smaller than 500 km².

2.1. ALHTAÏR Structure

The ALHTAÏR model includes three specific tools for producing floods hydrographs:

- The first tool, CALAMAR gives the rainfall data to the flash flood forecasting model.
- The second tool produces information about the watershed studied.
- Finally, ALHTAÏR software produces floods hydrographs in real time.

2.1.1. ALHTAÏR Module 1: CALAMAR

The CALAMAR tool models precipitations falling on each square kilometre of the study area, every five minutes. These images are georeferenced and calibrated, in real time (every five minutes), by the pluviometers in the Gard Region. The CALAMAR result (shown on Figure 2) is a georeferenced grid with the rainfall intensity value for each pixel (1 km²).

Some statistical tests were made to compare rainfall values obtained by radar images and by pluviometers. The comparison was made for rainfall greater than 40 mm. For 80% of the results, the difference between the two rainfall values is less than 30%. Corrected in real time with the rainfall recorder network, this data is sufficient for the flood-warning service of the Gard Region (Bressand, 2002).

2.1.2. ALHTAÏR Module 2: HYDROKIT

HYDROKIT is a Geographic Information System (GIS) that includes all watersheds and sub watersheds for the area under supervision of the SAC-30. With a Digital Elevation Model (DEM), HYDROKIT generates automatically the hydrographical parameters (hydrographical distance, slope,...) necessary to calculate the time of concentration. As previously, HYDROKIT generates a georeferenced grid with one square kilometre pixel.

2.1.3. ALHTAÏR Software

The ALHTAÏR software, is a hydrological flash flood forecasting model. The ALHTAÏR software interface is shown in Figure 3. It includes:

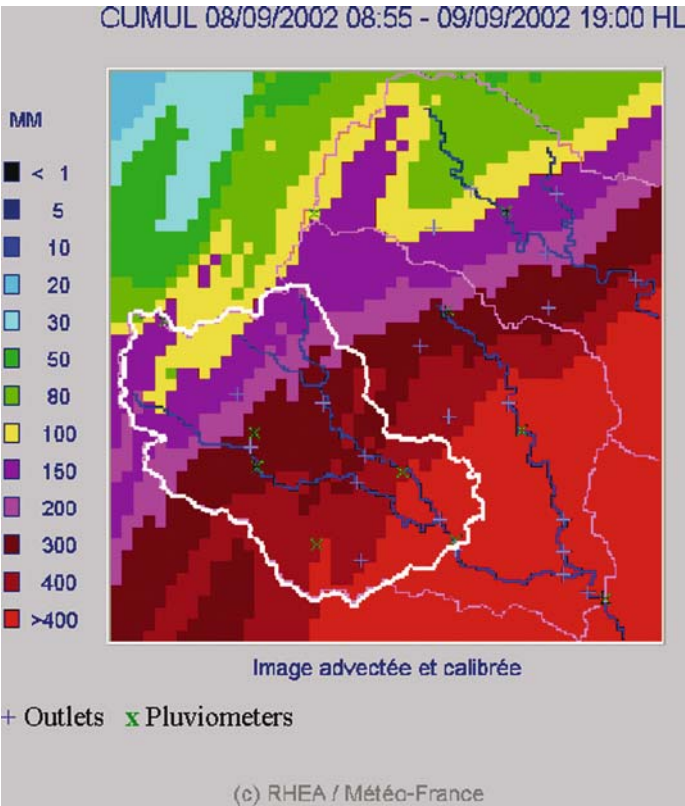


Figure 2. CALAMAR® georeferenced radar image

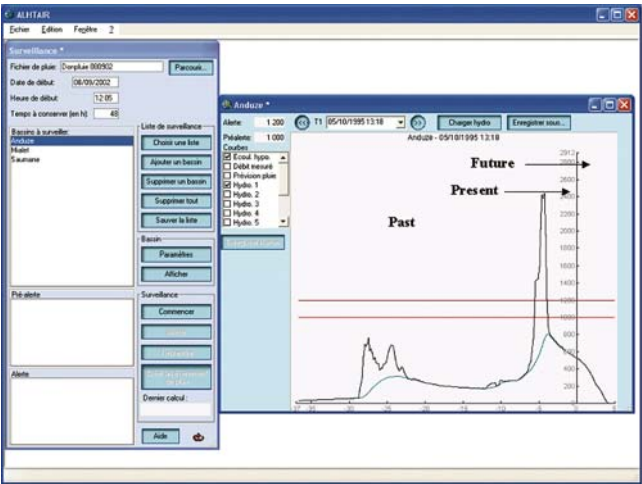


Figure 3. ALHTAIR Interface

- A production module (calculation of the effective rainfall), derived from the Horton principle (Horton, 1933). It allows to determine runoff according to the infiltration capacity.
- A propagation module (calculation of concentration time) that transfers the surface runoff at the outlet of the catchments provided by the HYDROKIT data. This model works in real time.

There are two versions of this flash flood forecasting model:

- The first one, ALHTAÏR in “watershed” mode, allows modification of the model parameters by catchments areas.
- The second one, ALHTAÏR in “spatialised” mode, allows model calibration, such as the infiltration capacity, according to the catchments spatial characteristics. ALHTAÏR in “spatialised” mode will be described in the second part of this paper.

2.2. ALHTAÏR in “Watershed” Mode

2.2.1. The propagation module

The propagation module is given by a law which transferring the surface runoff at the outlet. This law has been calibrated for the area under supervision of the SAC-30 (Bressand, 2002).

$$V = \left(1 + \frac{(p-1)}{9}\right) \cdot L^{0.25}$$

Where V is the celerity (m/s), p is the slope (%) and L is the hydraulic distance (km).

The quantity of runoff, which is calculated for a pixel, is propagated directly at the outlet each five minutes.

2.2.2. The production module

The production module of this flash flood forecasting model derives from the Horton principle, which explains the surface runoff by the excess of rainfall intensity in comparison to infiltration capacity. The infiltration capacity according to Horton is given by the following equation (Horton, 1933):

$$f(t) = f_c + (f_0 - f_c) \cdot e^{-kt}$$

Where f is the infiltration capacity (mm/h), f_0 is the initial infiltration capacity (mm/h), f_c is the final infiltration capacity (mm/h) and k (a constant) is an exponential decreasing coefficient until saturation.

When the rainfall intensity is greater than infiltration capacity, surface runoff occurs. But, this cannot alone explain the generation of all the flash floods in the Gard Region. Therefore the production module was modified (Bressand, 2002; Ayral and Sauvagnargues-Lesage, 2003). The process of this module is shown in Figure 4.

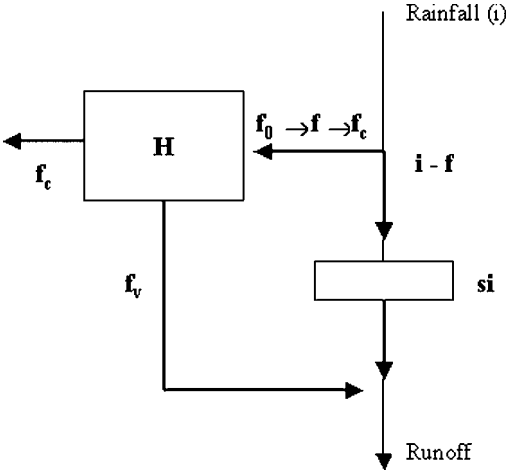


Figure 4. ALHTAÏR production module working

The rainfall intensity (i) is subtracted from the initial infiltration capacity (f_0) at the beginning of the rainfall event and then the infiltration capacity (f) is downgraded. Indeed, the initial infiltration capacity reduces according to time for tending to ground infiltration (f_c). The effective rainfall ($i-f$) must fill a volume (si), which represents a soaking rainfall. When this volume is full, all the effective rainfall contributes to the surface runoff. The subsurface flow (f_v) is generated by the “hortonian volume” (H) emptying, which contributes to the surface runoff. At the end of the rainfall event, the soaking rainfall volume empties. This calculation is made for each pixel, every five minutes.

The production module of ALHTAÏR has six parameters. Four of them can be calibrated (f_0 , f_c , f_v , and si), and two parameters are fixed (k and α).

It is possible to make a model calibration according to the studied watershed. But our objective is to work on small watersheds without gauging stations. So, the model calibration is identical for the area under supervision of the SAC-30 (Bressand, 2002). The parameter values are shown in Table 1.

The flash floods event of the Gard Region during September 2002 represents an extreme rainfall event, which allows evaluation of the experimental flash flood forecasting model ALHTAÏR.

Table 1. The module production parameter values obtained with the model calibration

The module production parameters of ALHTAÏR					
f_0 (mm/h)	f_c (mm/h)	f_v (mm/h)	si (mm)	k	α
90	4	15	0	0,575	3

3. EVALUATION OF THE FLASH FLOOD FORECASTING MODEL ALHTAÏR

The evaluation of the flash flood forecasting model ALHTAÏR is applied to small (10 to 100 km²) non-gauged watersheds only. The data used to make this evaluation are from the South East flooding in France in September 2002.

After a description of this extreme event, the methodology and the main results will be shown.

3.1. The Extreme Rainfall Event

On 8 and 9 of September 2002, the Gard Region, in South East of France was subjected to an exceptional meteorological event that led to catastrophic flooding as a result of its large extent, its violence and duration. Twenty-two people died during this catastrophe. Rainfall reached considerable values, as shown in Figure 5.

The greatest cumulated rainfall value observed was 687 mm in almost 24 hours in Anduze (near the little town of Alès, see Figure 1). Table 2 shows some cumulated rainfall values measured.

Similar rainfall has occurred in the last 100 years. Table 3 presents some rainfall values in the Gard and Mediterranean Region.

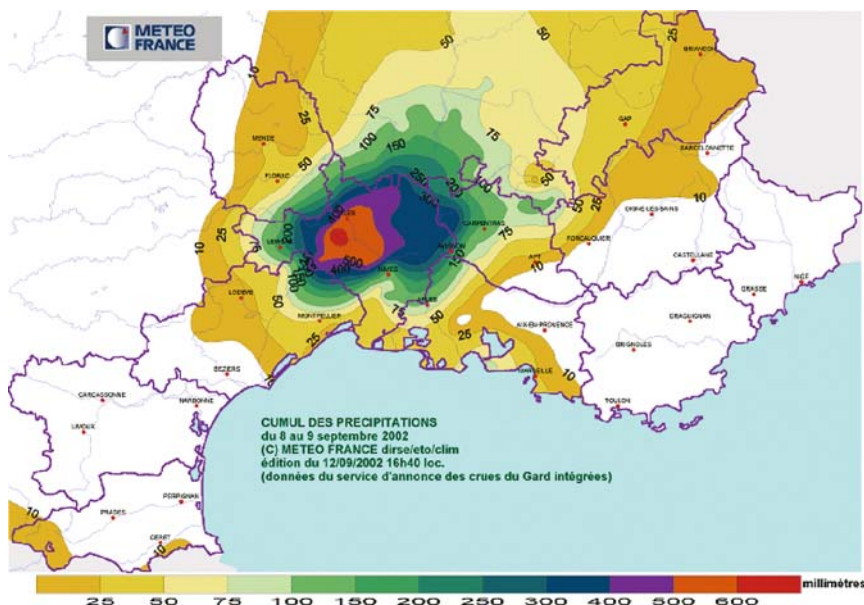


Figure 5. Rainfall accumulation during the September 2002 flooding

Table 2. Somer rainfall values in 24 hours during the 8 and 9 September 2002

Pluviometers location	Rainfall (mm)	Pluviometers location	Rainfall (mm)
Lunel	153	La Grand Combe	257
Alès	480	Remoulins	402
Anduze	687	Saint Hippolyte du Fort	325
Gajan	550	Uzès	418
Généralgues	589	Nîmes Courbessac	170

Table 3. Some historical rainfall values

Date	Rain recorder location	Duration	Rainfall (mm)
1825	Joyeuse (Ardèche Region)	24 hours	792
1890	Valleraugue (Gard Region)	24 hours	828
1900	Valleraugue (Gard Region)	24 hours	950
1940	Llau (Pyrénées Orientales Region)	23 hours	840
1940	St Laurent de Cerdan (Pyrénées Orientales Region)	5 days	1770
1958	Alès (Gard Region)	48 hours	500

The extent of this meteorological event and the flooding that followed can be explained by the combination of two types of phenomenon (Sauvagnargues-Lesage, 2004):

- Flash floods on all the rivers of the concerned area (including small rivers that are dry during the summer), in successive waves, and were amplified by river walls bursting
- Local streaming accumulation, in some places higher than 2 meters

About 4800 km² (corresponding to 295 districts) were affected area, together with the submersion of 80% of the roads, 20 bridges damaged or cut off, and a large number of complicated rescue operations (4200 rescue operations including 1300 safety operations by helicopters). The Gard Region restoration cost is estimated at 1.2 billion euros.

3.2. Materials and Method

To evaluate the efficiency of ALHTAÏR during this event, for small watersheds without gauging stations, it is necessary to use hydrological data acquired after this event, during the post event data collection and presented below. Then, the methodology of the comparison between the ALHTAÏR simulation and hydrological data estimation is described.

3.2.1. Post event analysis

After this extreme event, a data collection was carried out by research laboratories of the “Cévenne-Vivarais Mediterranean Hydro-Meteorological Observatory” (Delrieu et al. 2004).

The methodology which allows this post-event hydrological data collection was developed for previous flash flood events in the South-East of France (Gaume, 2002): Avène flash flood (tributary of the Gardon River) in October 1997 (Gaume et al. 2002) and Aude Region flash floods in November 1999 (Gaume et al. 2004).

After the September 2002 event, the methodology consisted of:

- Carrying out some flood victims interviews
- Estimation of peak discharges for some tributaries of the three principal Gard Region rivers Vidourle, Gardon and Cèze (see Figure 6)

More than 100 cross sections and 150 interviews were executed (Gaume et al. 2003b).

The interviews. Each witness interview was reported on a specific file georeferenced on a Geographic Information System. Interviews were based on open questions, for example: “tell us what happened”, “how fast did the water level rise?”, “When did the maximum occur?”. An example of these witness interviews is given in Figure 6.

River: The GRABIEUX (tributary of the Gardon d'Alès River)

Witness : 3 witness, 14 & 12 Jean Macé street, Jean-Moulin street

Coordinates : X=740 451, Y = 1 907 700 (Lambert II étendu)

Established by : G. Dumas, J. Goletto, J. Maffre (EMA), contact P.-A. Ayral (EMA)

Date : 29 & 30 janvier 2003

Description of the site : House located on the Grabieux river left bank, below of the ruisseau Rouge (brook) and the ruisseau blanc (brook) confluence, residential district

Map	Pictures

Summary of the interview:

- 7h – 7h10 : Maximum level of the water
- The rising stage has been very fast

Others observations:

- The water is not arrived in the garden.
- Maximum level of the water has been to 48 cm in comparison to garage level (witness 1, 14 Jean Macé street).
- Maximum level of the water has been to 75 cm in comparison to gate level (witness 2)

Figure 6. An example of interviews file

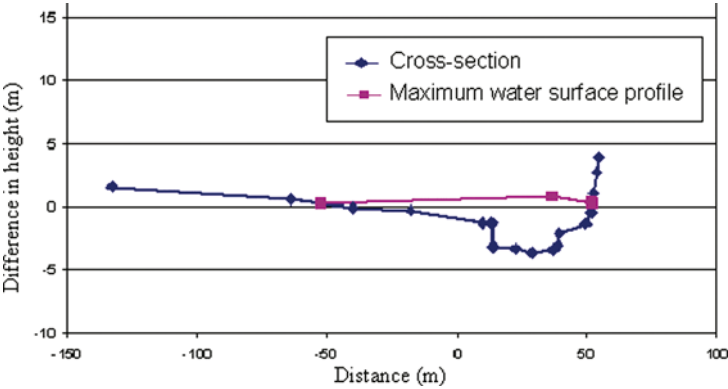


Figure 7. An example of river cross section

The objective was to collect as much information as possible about the chronology of the flood where no river stage record was available.

The peak discharge estimation. The peak discharge estimation requires a cross section of the river, a high water marks survey and a water surface slope. All these elements were measured with a theodolite. Figure 7 shows an example of the results of these measurements.

Then, the peak flow discharge was calculated by the Manning-Strickler formula (Gaume, 2002):

$$Q = K.R^{2/3}.I^{1/2}.S$$

Where Q is discharge (m³/s), K is the Strickler coefficient (m^{1/3}/s), R is the hydraulic radius (m), I is the surface profile slope (m/m) and S is the wetted area (m²).

For a better precision, the peak discharge was calculated for the three parts of the river (low flow channel, flood channel left bank and flood channel right bank). Table 4 presents the results of calculations.

Table 4. Example of peak flow discharge estimation for the Crespenou river cross-section

	K (Manning coef.)	Velocity (m/s)	Discharge (m ³ /s)
Low flow channel	20	2.92	166.3
Flood channel, left bank	15	1.14	58.8
Flood channel, right bank	10	0.90	47.2
Peak discharge estimation (m ³ /s)			
Minimum discharge estimation		200	
Maximum discharge estimation		350	
Probable discharge estimation		270	

The estimation quality is difficult to evaluate and there are several uncertainties:

- The post-event field measurements are difficult, notably the determination of the high water level.
- To apply the empirical Manning-Strickler formula, it is necessary to estimate the Manning-Strickler coefficient, which represents the roughness. This parameter has an important influence on the discharge estimation and is estimated by the “expert” that made the cross section.

Finally, the uncertainty of the peak discharge estimated is lower than $\pm 50\%$ (Gaume, 2002). This explains the fact that in Table 4, the minimum discharge estimation, the maximum discharge estimation and the probable discharge estimation are presented.

3.2.2. Watershed selection

To evaluate the efficiency of ALHTAÏR, several small watersheds were selected. Based upon the uncertainties in post-event data collection and peak discharge estimates. Twenty-one non-gauged watersheds were identified. Figure 8 shows the location of these watersheds.

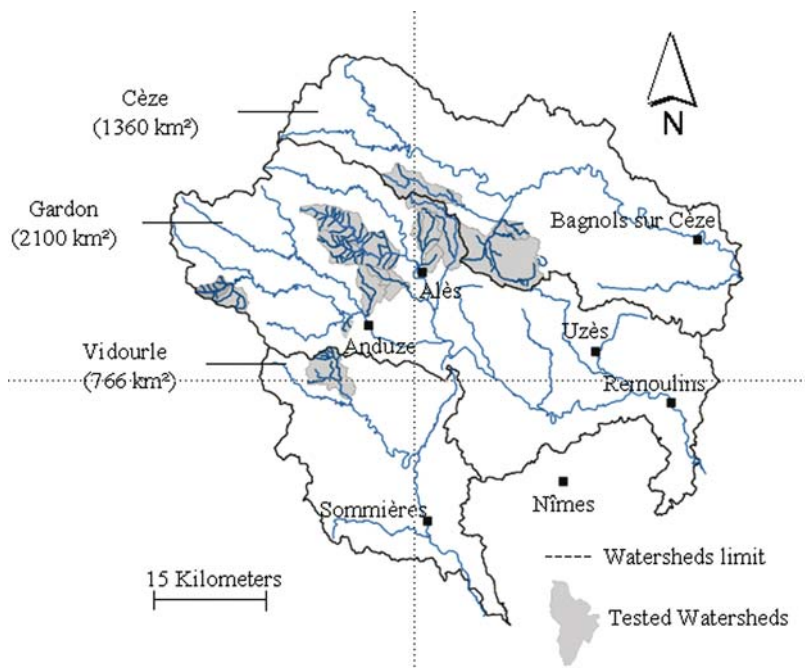


Figure 8. Location of test watersheds

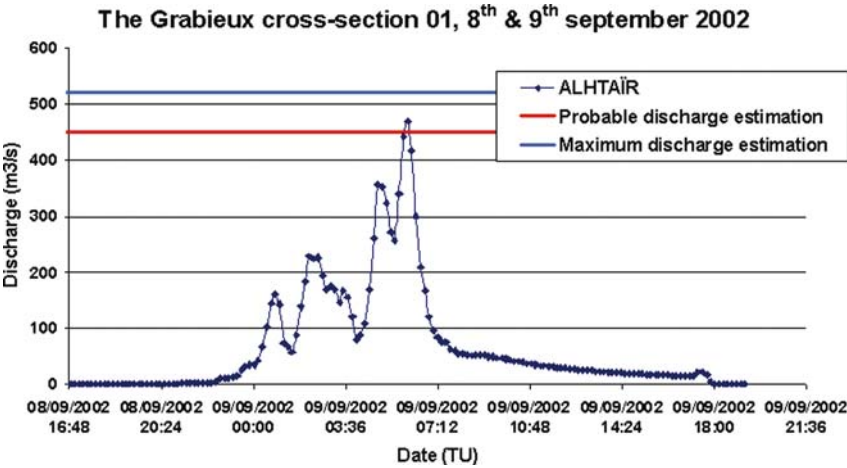


Figure 9. Results of the analysis for the Grabieux watershed
(*) –10 min: the peak flow discharge is forecast by the model ten minutes earlier than witness estimation

3.2.3. Watershed analysis

The watershed analysis requires three steps:

- The hydrograph is produced with the ALHTAÏR model for the September 2002 event.
- The peak discharge simulated is compared to peak discharge estimation (post-event data collection).
- The flood chronology (based on witness interviews) is shown on the ALHTAÏR hydrograph.

Figure 9 presents the three types of results for the *Grabieux* watershed.

After the watershed analysis, a GIS was used to characterise the tested watershed: surface, mean slope, geology and land cover were taken into account. A table of watershed information and the quality of the ALHTAÏR model response was compiled for each watershed. An example is given in Table 5.

Table 5. An example of characterisation of tested watershed

Watershed	Surface (km ²)	Slope mean (%)	Geology	Land cover	Overestimation underestimation of the peak flow discharge	Peak flow discharge chronology
Grabieux	21	3.7	Limestone and marl	Urbanized, agricultural parcels, evergreen oaks	+ 4 % to – 11 %	10 to 30 minutes fast

3.3. Results of the Evaluation of the Efficiency of ALHTAİR on Small Non-Gauged Watersheds During the September 2002 Event

This evaluation is based on three types of results that are presented below:

- Peak discharge estimation
- Peak flow chronology
- Watershed structure

3.3.1. Peak discharge estimation

The results of peak discharge estimation are quite good. Figure 10 shows these results for the twenty-one non-gauged watersheds (see Figure 8).

Generally, the model overestimates the peak discharge. For 16 watersheds, this overestimation is between 24% and 68%. However, the coefficient of determination (R^2) is equal to 0.94 for the comparison between maximum discharge evaluation and discharge simulation.

3.3.2. Chronology reconstruction

Only 9 watersheds were used to compare peak flow hour estimation with ALHTAİR, and peak flow hour given by witnesses. To do so several interviews are necessary for one watershed. For 7 watersheds the prediction is accurate (± 10 minutes), the maximum difference observed is about one hour (faster or retarded). The small number of tested watersheds and the variability of the witness estimation limit this analysis.

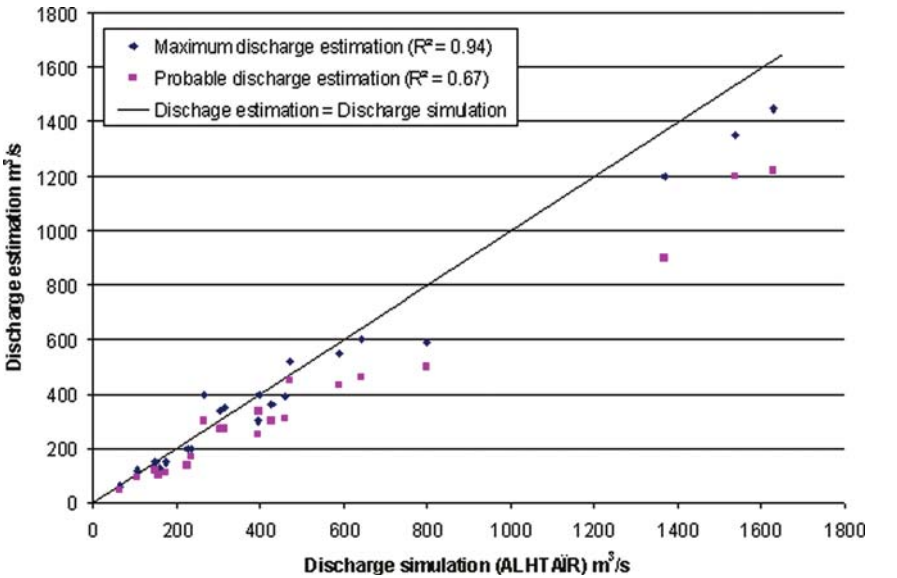


Figure 10. Comparison between discharge estimation and discharge simulation

Table 6. Comparison between peak discharge estimated/peak discharge simulated by watershed classes

Class	Geology / Land cover	D ¹ mean (%)	D min/max (%)	σ^2
1 (5 watersheds)	Limestone, marl / Urbanized, agricultural parcels, evergreen oaks	19	-12 / 60	24, 4
2 (7 watersheds)	Schist, micaschist / Chestnut trees, maritime pines	49	33 / 68	11, 8
3 (4 watersheds)	Limestone, marl, dolomite / Evergreen oaks	26	12 / 57	20, 9
4 (5 watersheds)	Limestone, dolomite / Evergreen oaks, maritime pines	36	24 / 38	6, 4

¹D = (Peak discharge simulated – Peak discharge estimated)/(Peak discharge simulated)

² σ = Standard deviation

3.3.3. Watershed structure

Relationships between the results of comparison between peak discharge estimation/peak discharge simulation and the watershed structure were studied. The watersheds were classified into 4 homogeneous classes according to geology and land cover, as shown in Table 6.

For classes 1 and 3, the results of ALHTAÏR simulations give very different peak discharges. For classes 2 and 4, the results of ALHTAÏR simulations appear to be more homogeneous.

The results are inconclusive because of small number of watersheds tested and because the estimated peak discharge includes significant uncertainties.

This first approach shows that for homogeneous watershed (geology/land cover) the forecasted peak discharges appear to be similar to observations (see Figure 9 and 10). On the other hand, for schistous watersheds, ALHTAÏR overestimates the peak discharge (+ 49%). For calcareous watersheds, the overestimation is lower (36%).

This first application of the ALHTAÏR model to non-gauged watersheds shows the potential to improve ALHTAÏR with a spatial approach.

4. DISCUSSION

The hydrological data collected after the extreme event of September 2002 is a first study of the response of ALHTAÏR applied to the non-gauged watersheds. The flash flood forecasting model appears to overestimate the peak discharge even if the chronology of flood appears to be well reconstituted, as shown in Figure 11.

4.1. About ALHTAÏR in “Watershed” Mode

In order to confirm the previous results, two supplementary studies were conducted:

- ALHTAÏR in “watershed” mode was tested in operational conditions at the flood warning service of the Gard Region (SAC-30) during the September 2002

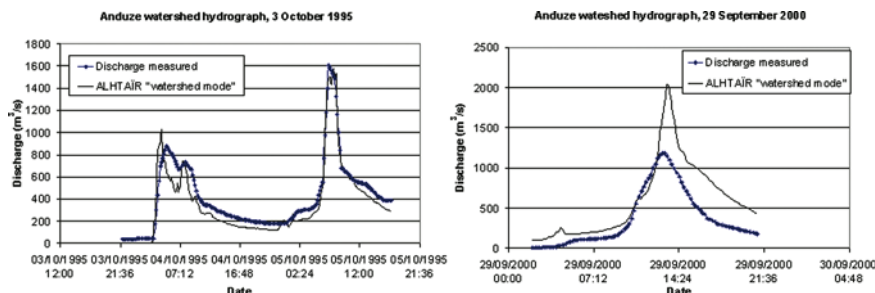


Figure 11. Anduze watershed hydrographs in October 1995 and in September 2000

flooding. The overestimation of the peak discharge seems to be confirmed for the gauged watersheds.

- ALHTAIR was tested on few past flash flood events. Results show the same overestimation (Ayrat and Sauvagnargues-Lesage, 2003). The Figure 13 presents two hydrographs for two different events on the Anduze watershed (see location on Figure 1).

The overestimation was shown for the non-gauged watersheds. As a result, it appears that further improvement of this model is required.

4.2. Spatialisation of the Forecasting Model

A possible explanation of the overestimation of the peak discharge is the watershed structure. A new version of ALHTAIR model was developed in "spatialised" mode. The differences concern the production module parameters:

- They are determined by a spatial analysis
- They are differentiated according to the physical characterisation of the watershed, according to the infiltration capacity in particular

The main parameter of the production module is the infiltration capacity: f_0 (Ayrat et al. 2004). This infiltration capacity depends on several characteristics of the watershed, for example geology, pedology or land cover. A specific methodology was developed to determine the infiltration capacity. Figure 12 presents this methodology.

This methodology is a combination of an analysis of the available information layers on the watersheds with several experimental field tests in order to differentiate the homogeneous areas identified by previous GIS analysis. Finally, the model calibration is presented with map, of the whole Gard Region.

4.3. First Tests with ALHTAIR in "Spatialised Mode"

A first campaign of field tests (Desprats et al. 2003) was done on the watershed of the *Anduze Gardon River* (see Figure 1). The first results enabled development of

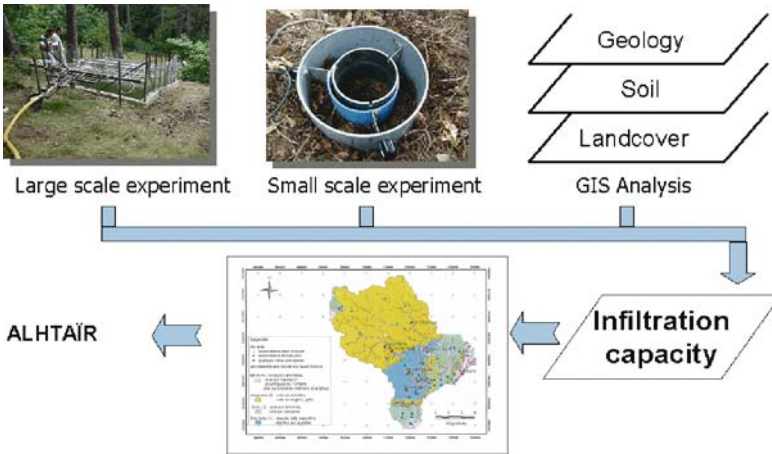


Figure 12. Spatialisation of ALHTAIR model

an infiltration capacity layer (see Figure 12) including four classes of permeability. The infiltration capacity (f_0) was calibrated according to the 4 classes. Figure 13 shows the ALHTAIR model simulations for the October 1995 and September 2000 events on the Anduze watershed in the “watershed mode” and “spatialised mode”.

For the 29 September 2000 event, the use of ALHTAIR in “spatialised” mode seems to improve the hydrograph forecast (1190 m³/s measured – 1577 m³/s simulated).

For 3 October 1995, the results are more difficult to explain. The spatialisation improves only a part of the hydrograph (first and second peak flow). For the third peak flow, the simulation with ALHTAIR in “spatialised” mode underestimates the measured hydrograph. These results can be explained by the quality of radar images, which are better for 2000 than for 1995. The influence of this information in the flash flood forecasting model is significant (Ayral et al. 2004; Ayral and Sauvagnargues-Lesage 2003).

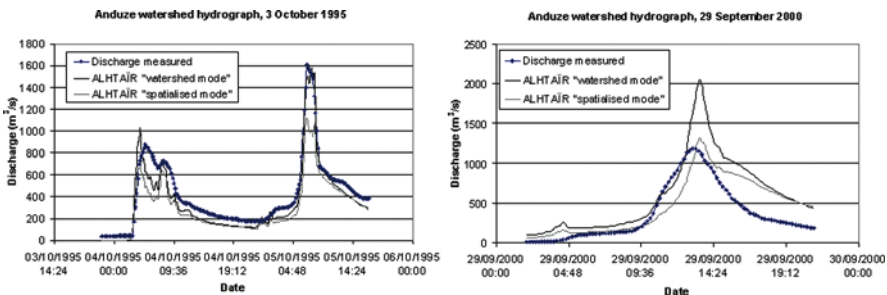


Figure 13. Comparison between ALHTAIR in “watershed” mode and “spatialised” mode

Moreover, it is necessary to continue these tests with a rainfall events database. The methodology to compute images in order to obtain rainfall data must be harmonized. At the same time, the cartography of the infiltration capacity must be improved with a new campaign of field tests. However, the first results presented in this paper show the usefulness of this kind of forecasting model for flash floods, in emergency situations.

5. CONCLUSION

The main objective of this study was to spatialise the flash flood forecasting model ALHTAÏR. Two methodologies were used:

- The collection of hydrological data after extreme events
- The computation of an infiltration capacity map

Currently, ALHTAÏR model both in “watershed” mode and “spatialised” mode is in research and development phase, and it has been also tested in the flood-warning service of the Gard Region (SAC-30), in real time processing.

The floods of the Gard Region during the 8th and 9th September 2002 allowed the ALHTAÏR forecasting capacity on the small non-gauged watersheds to be studied. The model seems to overestimate the peak discharge, but the chronology seems to be respected. These results need to be verified by other rainfall events less extreme than September 2002.

However, the spatialisation of the flash flood forecasting model ALHTAÏR appears to improve its efficiency. Improving the infiltration capacity map would allow a better spatialised model calibration.

The flash flood forecasting for the non-gauged watersheds is an important challenge for the Mediterranean coast. The past event analysis, and the spatialisation of this forecasting model are two encouraging approaches.

ACKNOWLEDGEMENTS

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CHAPTER 19

FLOOD FORECASTING FOR THE UPPER AND MIDDLE Odra RIVER BASIN

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Abstract: The objective of the authors' work in the area of flood forecasting and distributed modelling is to determine how different model formulations and different rainfall inputs contribute to forecast accuracy and uncertainty. To address these issues within the EU project FLOODRELIEF, a comprehensive distributed catchment model has been formulated and tested for the upper and middle Odra River. Within the FLOODRELIEF project multiple distributed modelling approaches, including the model presented here, are being developed for the Odra basin. The objectives of developing these different modelling approaches are; to evaluate the performance of these different models in representing the catchment processes and river flows, to examine the effect of model structure on the character of flow simulation and prediction uncertainty and to examine the sensitivity of these models to different rainfall input

The Odra basin was selected for these analyses as a flood-prone catchment representing highly developed European catchments where comprehensive modelling of the river system, flood plains, polder subsystems, and structures as well as rainfall-runoff and snowmelt processes in the tributary catchments are required. Flood forecasting in the Odra requires both fast and reliable simulations for this complicated river basin and therefore a careful balance between accurate representation of the catchment flood processes, the flood wave movement and inundation extent and the need for rapid forecasts

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This paper describes the formulation, calibration, validation and real-time implementation of an operational distributed model for flood forecasting for the upper and middle Odra. This application shows that the MIKE 11 distributed model is able to reproduce the large-scale rainfall-runoff processes and the propagation of the flood wave through the main river channel system including the catastrophic flood of July 1997. This model is therefore suitable as a reference for the evaluations of different models and model structures in our investigations of simulation and forecast uncertainty. A model post-audit was carried out which identified cases where simplified representations in the rainfall-runoff models that performed well in the calibration, requires revision for the validation period. This type of post-audit analysis is extremely valuable in evaluating model performance and ensuring continuing improvement in flood forecasting accuracy

Keywords: Upper and Middle Odra, distributed hydrological modelling, flood forecasting, model calibration and validation, flow simulation uncertainty

1. BACKGROUND

In July 1997, the Odra River basin was struck by an extreme flood event (Dubicki, 1998; Bronstert, et al., 1998), seriously affecting the Czech Republic, Poland and Germany. In Poland alone more than 160,000 people were evacuated and damages estimated to be more than 5 billion EURO, Grunewald (1998). Floods are not rare on the Odra, with major floods recorded in 1813, 1838, 1854, 1870, 1903, 1938, 1939, 1958, 1965, 1970, 1972, 1977, 1981 and 1985. However in the upper part of the Odra, the headwaters in the Czech Republic and the mountainous tributaries in the Czech Republic and Poland, the 1997 flood was an extremely rare event. In the upper Odra, its upstream tributaries and Nysa Kłodzka, exceptionally rapid rises in water level were experienced with observed water levels and discharges exceeding all previously observed maximums, (Dubicki, 1998). Further downstream flooding of the large towns of Opole (131,000) and Wrocław (700,000) caused high material losses as the urban flood protection systems then in place were conceived for a far lower design flow, (Grunewald, 1998). The economic losses were mainly concentrated in the upper and middle Odra river basin. In four former voivodships: Katowice, Opole, Wrocław, Wałbrzych; economic loss sum total reached 85 % of the total economic loss in the whole Odra catchment, (Chojnacki, 1998).

The main cause of the flooding was the combination of both intense and long-lasting rainfall on the catchments. The rainfall occurred in two periods in early and mid-July and the rain that occurred was exceptional in intensity, duration and areal coverage. This led to a rapid rise in flow in the Odra and overlapping flood waves in its tributaries. Alarm levels were continually exceeded for a period of several weeks. A more complete discussion of the meteorological situation leading to this flood event is given in (Dubicki, 1998; Malitz, 1998). The magnitude of the resulting flood was unexpectedly high. There are a number of large towns along the Odra in Poland, such as Racibórz, Kędzierzyn-Koźle, Opole, Wrocław, Głogów, Nowa Sól, Słubice, Szczecin and urban flooding caused the majority of material losses.

Losses cannot be avoided when major floods occur but flood preparedness can help reduce flood damage and the number of lives lost. Flood forecasting, in particular, provides an opportunity to reduce the impacts of flood events at a relatively low economic and environmental cost. One of the major recommendations from the European Expert meeting on the 1997 Odra flood, (Bronstert, et al., 1998), was the need to provide improved flood forecasting for flood management.

This paper describes the development, calibration and validation of a distributed hydrological and hydrodynamic model for the upper and middle Odra, together with its implementation in an operational flood forecasting system. This study is part of a more general investigation into hydrological simulation accuracy and uncertainty. The Odra River is highly developed and is characterised by a complex river network, a large number of fixed and moveable hydraulic structures (more than 95 on the main river and approximately 430 when all tributaries are included) as well as 14 flood storage reservoirs (polders). The moveable structures are operated for navigation during low flows, with special operating rules during flooding. The polders are used as active flood mitigation reservoirs during high flow, and these too are controlled by both fixed and moveable structures. In addition, there are several reservoirs in the upstream portions of the basin. Accurate flood forecasting requires comprehensive modelling of the river system, flood plains, polder subsystems, reservoirs and structures.

As pointed out above overlapping tributary flows from the mountainous catchments along the southern border contributed significantly to the flooding in the main river during the 1997 events. These mountainous catchments respond at much smaller time scales and therefore require rainfall-runoff modelling of the tributary catchments. In addition it is important that snowmelt effects be accounted for. Flood forecasting in the upper and middle Odra requires a combination of rainfall forecasting, rainfall-runoff and snowmelt modelling as well as hydrodynamic river modelling to satisfactorily represent the different flood processes occurring at different time scales within the basin.

2. MOTIVATION

Distributed hydrological modelling has the potential to improve estimates of streamflow and water levels both for hydrological simulation and for flood forecasting (Smith et al., 2004). The increased focus on distributed modelling approaches to flood forecasting is motivated by increasing access to high resolution operational rainfall estimates by meteorological modelling, radar and satellite remote sensing, as well as GIS databases of catchment properties and increasing computer power. One of the central objectives of the EU 5th framework project (<http://projects.dhi.dk/floodrelief/>) FLOODRELIEF is to develop improved methods for flood forecasting by exploring new approaches to distributed modelling and to investigate the uncertainty associated with distributed hydrological modelling (Butts, 2003; Butts et al., 2004). Uncertainty in the model structure, model parameters and the rainfall estimates which constitute the main input to the models are

significant sources of uncertainty that affect the accuracy of distributed hydrological models over a wide range of space and time scales. An important science question is what role do these different sources of uncertainty play in the realisation of benefits from distributed models?

Within the FLOODRELIEF project, the Odra basin was identified as a study basin in which different distributed modelling approaches are being used to explore what improvements in flood forecasting can be achieved using the different distributed models. The ability of the different model structures to represent the catchment processes and flood wave propagation will be examined to develop improved hydrological simulations. Many studies have examined the issue of model parameter uncertainty and rainfall uncertainty but relatively few have examined systematically the impact of model structure error and complexity on model performance and uncertainty.

While distributed modelling has a number of potential benefits it appears that further work is required to achieve this potential for operational modelling. [Refsgaard and Knudsen \(1996\)](#) compared a complex distributed model, a lumped conceptual model, and an intermediate complexity model on data-sparse catchments in Zimbabwe. Their results could not strongly justify the use of the complex distributed model. [Bell and Moore \(1998\)](#) evaluate variants of a simple grid-based distributed model against a lumped model used operationally in the UK. They find that a well-designed lumped model is preferable for operational purposes. A recent study initiated by the US National Weather Service Distributed Model Inter-comparison Project (DMIP) represents perhaps the first organised and published comparison of distributed models amongst themselves and to a widely used lumped model, [\(Smith et al. 2004\)](#). The main goals of DMIP were to understand the capabilities of existing distributed modelling methods, identify promising directions for future research and development and to answer questions like; What level of model complexity is required to realise improvement in basin outlet simulations? One of the key findings, [\(Reed et al. 2004\)](#) was that “although the lumped model outperformed distributed models in more cases than distributed models outperformed the lumped model, some calibrated distributed models can perform at a level comparable to or better than a calibrated lumped model (the current operational standard. ”. These results suggest that further work is required in exploring different distributed model formulations. Within the FLOODRELIEF project, a general modelling framework has been developed, which allows alternative model structures for the rainfall-runoff processes and channel routing to be explored [\(Butts et al., 2004\)](#). However it is important to define a reference case. In the DMIP study lumped operational models were used as this reference. For many operational flood forecasting systems a more complex distributed modelling approach is required. The catchment-based distributed model described here will be used as the reference case for the FLOODRELIEF investigations. This paper evaluates the performance of this reference model for hydrological and hydrodynamic simulations of the upper and middle Odra basin.

3. MODELLING THE UPPER AND MIDDLE ODRA BASIN

The following section describes modelling of the Odra Basin using the MIKE 11 river and catchment modelling system. The purpose of this model was to provide operational flood forecasts for the tributary inflows and the river flows and water levels within the main channel of the upper and middle Odra. MIKE 11 is a modelling system for the simulation of flows, sediment transport and water quality for rivers, flood plains, irrigation systems, estuaries and other water bodies, (Havnø et al., 1993). The different processes are treated in an integrated modular structure. For river basin modelling, the channel flow module (HD) is used to model discharge, water levels, control structures in river networks, reservoir, lakes and tidal inlets. This hydrodynamic (HD) module contains an implicit finite difference computation of unsteady flows in the rivers based on the Saint Venant equations. The formulation can be applied to branched and looped networks and quasi two-dimensional flow simulation on flood plains. The rainfall-runoff (RR) module is used to model the transformation of rainfall to runoff within a catchment or a number of subcatchments.

3.1. Continuous Rainfall-Runoff Modelling

For many hydrological applications where continuous rainfall-runoff modelling is required, including real-time flood forecasting, the NAM model, an option in the RR module has been widely used, (Butts et al., 2001; Madsen, 2000; Refsgaard, 1997; Havnø et al., 1993). When applied to a single catchment this model can be characterised as a deterministic, lumped conceptual model that operates by continuously accounting for the moisture content in a number of different but mutually inter-related storages, Figure 1 and (Nielsen and Hansen (1973). The main parameters used in the calibration of the NAM model are listed in Table 1 and a more detailed description of this model can be found in the references cited above.

In most applications, the basin of interest is divided into a number of sub-basins in order to represent the spatial variations in either the meteorological forcing or sub-basin characteristics, The runoff from these basins then becomes the inflow to the river or channel network. The upper and middle Odra catchment model has been subdivided into 23 sub-catchments as shown in Figure 2. The model encompasses a total catchment area of about 40,000 km². The size and number of subcatchments used was determined primarily by the need to provide forecasts of the major tributary inflows to the main river, where the rainfall-runoff sub-models could be calibrated and validated and the resolution of the rain gauge network. As the focus of the model development was forecasting in the main river system, a detailed representation of the river structures and reservoir was incorporated into the river model. However a simpler representation was chosen in the tributary catchments where the presence of many of the structures (there are more than 430 in total) complicate the hydraulic description within these subcatchments. This was done for two reasons. Firstly, rapid operational forecasts

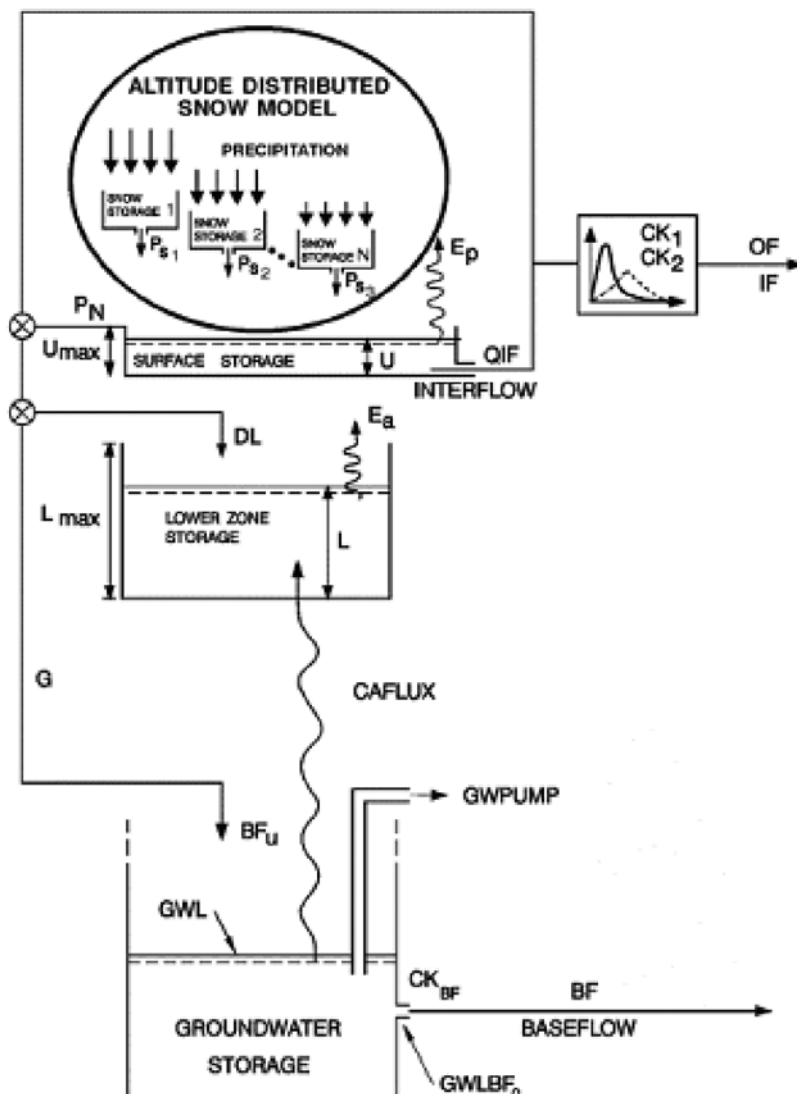


Figure 1. Structure of the NAM with the extended altitude distributed snow model

were required. Since the purpose of the rainfall-runoff models was to represent main tributary inflows rather than detailed forecasts within the subcatchments, a simpler representation was justified and would result in faster model calculations. Secondly for large flood events, like the 1997 event, the impact of these structures was expected to be limited particularly when representing large subcatchments. Instead of representing these structures explicitly, they are represented conceptually by the storages

Table 1. Main NAM model parameters and their physical interpretation

Para-meter	Units	Description
$U_{\max}$	mm	Maximum water content in the surface storage. This storage can be interpreted as including the water content in the interception storage, in surface depression storages, and in the uppermost few cm's of the soil
$L_{\max}$	mm	Maximum water content in the lower root zone storage. $L_{\max}$ can be interpreted as the maximum soil water content in the root zone available for the vegetative transpiration
CQOF	-	Overland flow runoff coefficient. CQOF determines the distribution of excess rainfall into overland flow and infiltration
TOF	-	Threshold value for overland flow. Overland flow is only generated if the relative moisture content in the lower zone storage is larger than TOF
TIF	-	Threshold value for interflow. Interflow is only generated if the relative moisture content in the lower zone storage is larger than TIF
TG	-	Threshold value for recharge. Recharge to the groundwater storage is only generated if the relative moisture content in the lower zone storage is larger than TG
CK_{IF}	hours	Time constant for interflow from the surface storage. It is the dominant routing parameter of the interflow because $CK_{IF} > CK_{1,2}$
$CK_{1,2}$	hours	Time constant for overland flow and interflow routing. Overland flow and interflow are routed through two linear reservoirs in series with the same time constant $CK_{1,2}$
CK_{BF}	hours	Baseflow time constant. Baseflow from the groundwater storage is generated using a linear reservoir model with time constant CK_{BF}

within the rainfall-runoff model. The delineation of the tributary catchments has been based on the topographical boundary upstream of a reliable discharge gauging station as shown in Figure 2. These catchment outflows are included as point inflows to the river network. The nine riparian catchments along the main channel have been delineated for each 50–100 km length of river based on the topographical area between two gauging stations. In this case the inflow is distributed along the length of the river.

The meteorological data requirements of the rainfall-runoff calculations are time series of precipitation, potential or reference evapotranspiration and temperature for snow melt modelling. A three-year period from 1995–1997, including the July 1997 flood event, was used for calibration. For this period daily values of rainfall were available from 85 stations throughout the model area. Subcatchment mean rainfall was derived using a straightforward weighting scheme typically based on the nearest 4–5 rain gauges. In the mountainous subcatchments it was recognised that the catchment mean rainfall would be underestimated if based solely on the rain gauge values. This occurs because most of the rain gauges are situated in more accessible low altitude locations and the higher altitudes are under-represented. Analyses of rainfall records show a clear trend in the precipitation, with an average

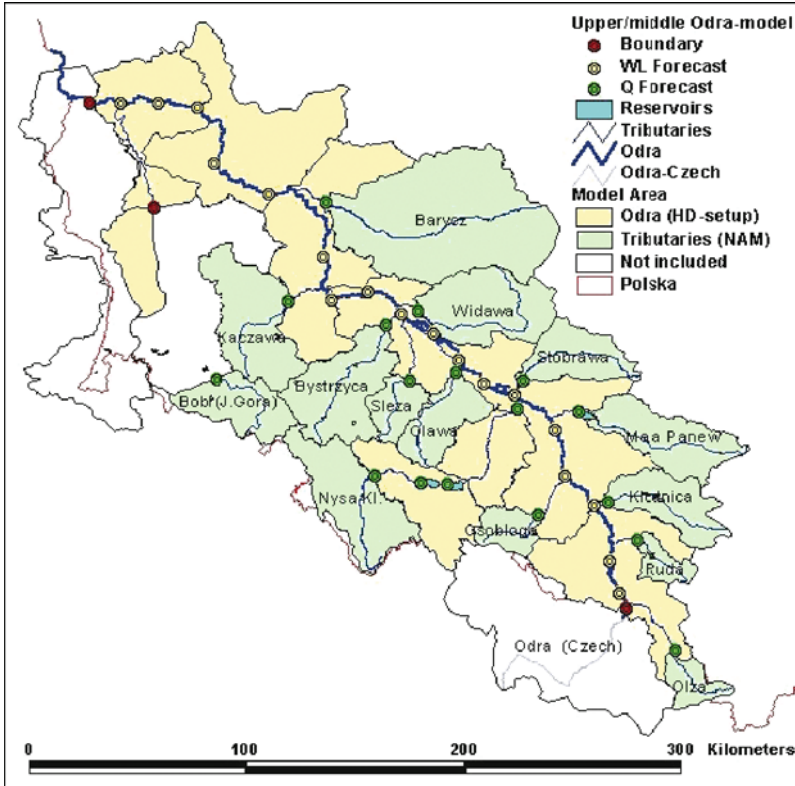


Figure 2. The catchment delineation and river network used for the upper and middle Odra

increase of 9% for each 100m increase in elevation. This correction was used within the model to treat both rainfall and snow accumulation in elevation zones.

A new feature implemented in the NAM model for this application was an altitude distributed snow model, Figure 11. In mountainous areas, temperature, precipitation, and snow cover vary significantly within a single catchment, but are often strongly dependent on altitude. The runoff simulation for such areas can be improved by sub-dividing the catchment into smaller zones and maintaining individual snow storage calculations for each zone. Since in many cases the hydro-meteorological information from mountain basins is quite sparse, the approach includes facilities for distribution of meteorological information with altitude. The area of each of the altitude zones was extracted from a digital elevation model. The approach for melting and accumulation of snow is based on WMO (1986) and Gottlieb et al. (1980).

Daily values of reference or potential evapotranspiration were estimated from a limited number (six) of synoptic meteorological stations in the model area and for each subcatchment the nearest representative station was used. This is expected to

Table 2. Yearly accumulated reference or potential evaporation (mm) for the synoptic stations in the model area

Year	Zielona Gora	Leszno	Legnica	Wroclaw	Bielsko-Biala	Racibórz
1995	641	658	671	646	624	594
1996	536	559	570	551	570	483
1997	618	643	643	632	604	583
1998	606	614	645	636	-	616
1999	623	613	632	630	-	587
2000	600	609	600	631	-	593
2001	576	558	565	561	-	560

provide an acceptable representation of the reference evapotranspiration (ET) in the different subcatchments as the spatial variability of reference ET is smaller than for example rainfall and occurs over much larger scales. This is reflected in the annual values from these stations listed in Table 2.

4. CALIBRATION AND VALIDATION OF THE UPPER AND MIDDLE Odra MODEL

A split sample strategy has been applied to evaluate the model performance. The calibration period covers the interval between 1st Jan 1995–1st August 1997 including the major flood during July 1997. The model development, this calibration and the establishment of operational forecasting was carried out immediately after the 1997 flood, within a project supported by the Danish Environmental Protection Agency (DEPA). The selection, several years later, of the Odra basin as a study catchment in the EU project FLOODRELIEF provided an interesting opportunity to perform an independent evaluation of the operational model or post-audit, (Konikow, 1986). A post-audit provides a simple mechanism in which the ability of a hydrological model to accurately represent the catchment processes can be evaluated and improved. The validation or post-audit period covers the interval between 1st Dec 1997–1st October 2001.

The calibration of the upper and middle Odra was carried out in two steps. The first step involved the calibration of the rainfall-runoff model NAM for the tributary subcatchments against measured flow at the subcatchment outlets. The catchments used for model calibration are shown as the darker grey upstream subcatchments in Figure 2. This was carried out using automatic calibration methods. The next step was to calibrate both the rainfall-runoff models for the riparian subcatchments along the main river, shown as lighter grey subcatchments and the calibration of the river channel or hydrodynamic model. For the riparian subcatchments the flows at the outlet are a combination of river flows through the upstream river boundary and runoff from rainfall falling within the subcatchment. Therefore a separate river model was developed for calibration consisting of the river network and only these riparian subcatchments. The measured flows were used as the

channel boundary conditions. In this second step initial parameters for the rainfall runoff model were estimated from the neighbouring lowland calibration catchments. Starting at the upstream end of the main river, the surface parameters controlling the peak flows and timing (in particular $U_{\max}$, $L_{\max}$ and $CK_{1,2}$ see Table II), were adjusted manually until a good match was found between the observed and simulated discharge. At the same time, calibration of the hydrodynamic model was carried out by comparing with both the observed discharge and observed water levels at points along the river. The hydrodynamic calibration was carried out either by adjusting the floodplain schematisation, the flow resistance on the floodplains or in the river channels, the operation of hydraulic structures, or a combination of these exploiting local knowledge of the river behaviour. This was carried out manually using an iterative procedure, as changes to parameters in both the rainfall-runoff model and the hydrodynamic model will affect the timing and magnitude of the peaks.

4.1. Rainfall-Runoff Model Calibration and Validation

The parameters of conceptual models like NAM cannot, in general, be obtained directly from measurable quantities of catchment characteristics, and hence model calibration is needed. In this case calibration of the rainfall-runoff model for the fourteen upstream gauged catchments was carried out using the automatic calibration facilities available within the rainfall-runoff module, (Madsen, 2000). This automatic calibration is based on the shuffled complex evolution (SCE) algorithm (Duan et al, 1992). The SCE model has been widely applied and several studies have demonstrated that the SCE method is an effective and efficient search algorithm, (e.g. Duan et al, 1992; Kuczera, 1997). The parameters derived by this process are of course dependent on the spatial scale of the subcatchment discretisation used. For conceptual hydrological models like the NAM model, the dependence of the calibrated conceptual storage capacities and the resulting model flows on the spatial scale, caused by the spatial variability of rainfall is well-known, (Finnerty et al, 1997).

For validation, a very strict application of the split sample test is applied. No changes were made in the parameters. Time series data for the validation period were then used in all calibration subcatchment models. However, several rain gauge stations available for the calibration were closed down in the validation period. Two possible approaches were considered. Additional rain gauges adjacent to the catchment could be used to replace those used in the calibration but not available in the validation period. Alternatively, the same gauges could be used but the weights applied to each gauge increased proportionately where a gauge was found to be missing. This second strategy was adopted for the validation results shown here for two reasons. Firstly this second strategy was already used if data is missing for short periods in the calibration data and if there is missing data from rain gauges in the operational forecasts. So the impact of the strategy on model performance is interesting from an operational viewpoint. Furthermore as this approach does not

introduce any new data it represents a strict test of the calibration. For the reference potential evapotranspiration the same approach was not possible. As shown in Table 2, data from the most representative synoptic station at Bielsko-Biala which was used in the calibration was unavailable after 1997. In this case the station at Racibórz was used instead of Bielsko-Biala in the validation period.

The performance of the model in calibration period and subsequent post-audit are presented through statistical summaries for the calibration and validation period, water balances and hydrographs. Figure 3 to Figure 8 present the observed and simulated hydrographs at the outlet of three of the calibration subcatchments. The subcatchment results are given for 1) the subcatchment upstream of the Jelenia Gora station on the Bobr river, 2) the subcatchment upstream of the Bardo station on the Nysa Klodzka river and 3) the subcatchment upstream of the Staniszcze station on the upper Mala Panew river, Figure 2. The first two are predominantly mountainous subcatchments close to the southern Polish border on the left of the Odra river while the Mala Panew is representative of the lower and flatter tributary

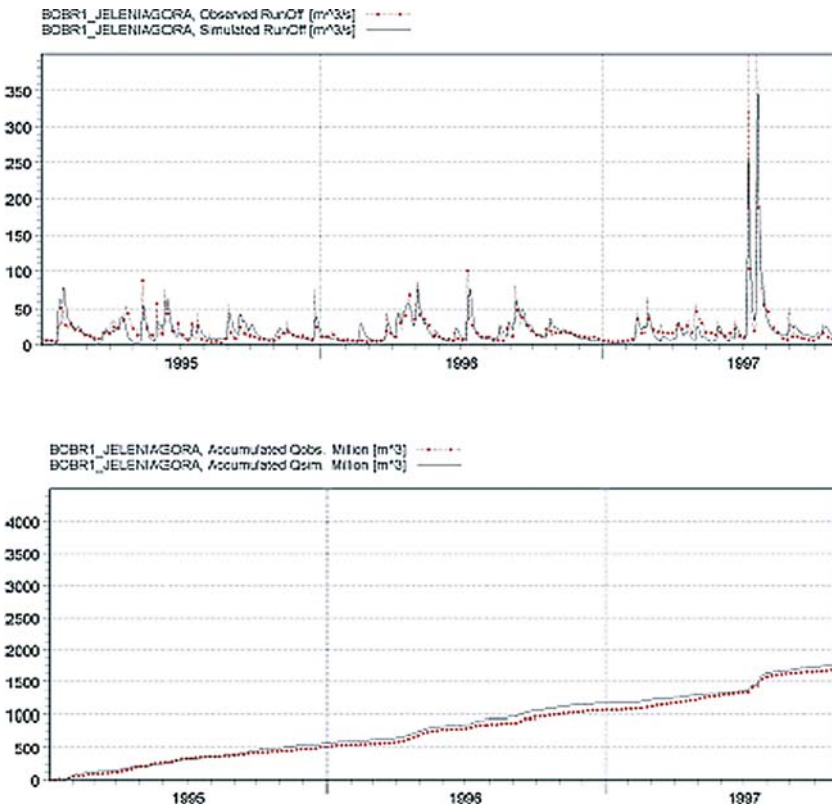


Figure 3. Measured (symbols) and simulated (line) discharge hydrograph and accumulated water balance for the calibration period for the Jelenia Gora station on the Bobr River

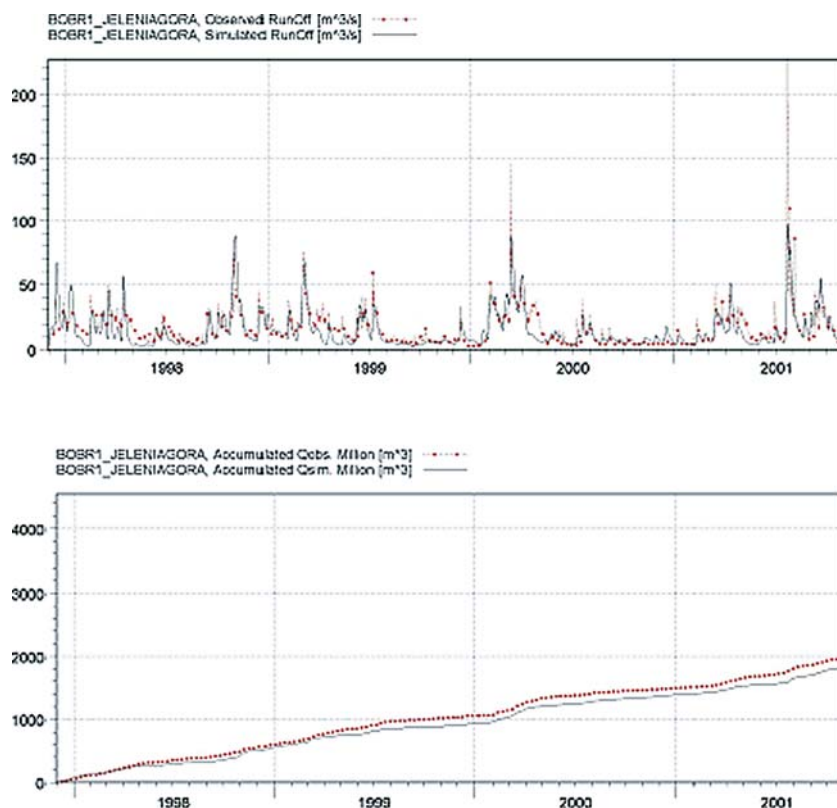


Figure 4. Measured (symbols) and simulated (line) discharge hydrograph and accumulated water balance for the validation period for the Jelenia Gora station on the Bobr River

subcatchments on the right of the Odra. In each case the upper figure compares the discharge hydrograph and the lower figure shows the accumulated water balance over the same period. For each of these tributary catchments the results for the calibration period are presented first and the performance for the validation period shown immediately afterwards.

The figures show that the response in the mountainous subcatchments includes more frequent and more rapid event hydrographs than observed in the lowland catchment but the rainfall-runoff model can represent both types of catchment response. As can be seen from these figures the timing and magnitude of the flood hydrographs are captured reasonably well. The extreme flood in July 1997 dominates flow hydrographs in the calibration period.

While the peak flows in the validation period are not as large as 1997 event, significant events in 1998, 2000 and especially in 2001 were observed. From a visual inspection of these curves, the results for the calibration period and the 1997 event are satisfactorily represented. This is confirmed by Table 3, which presents

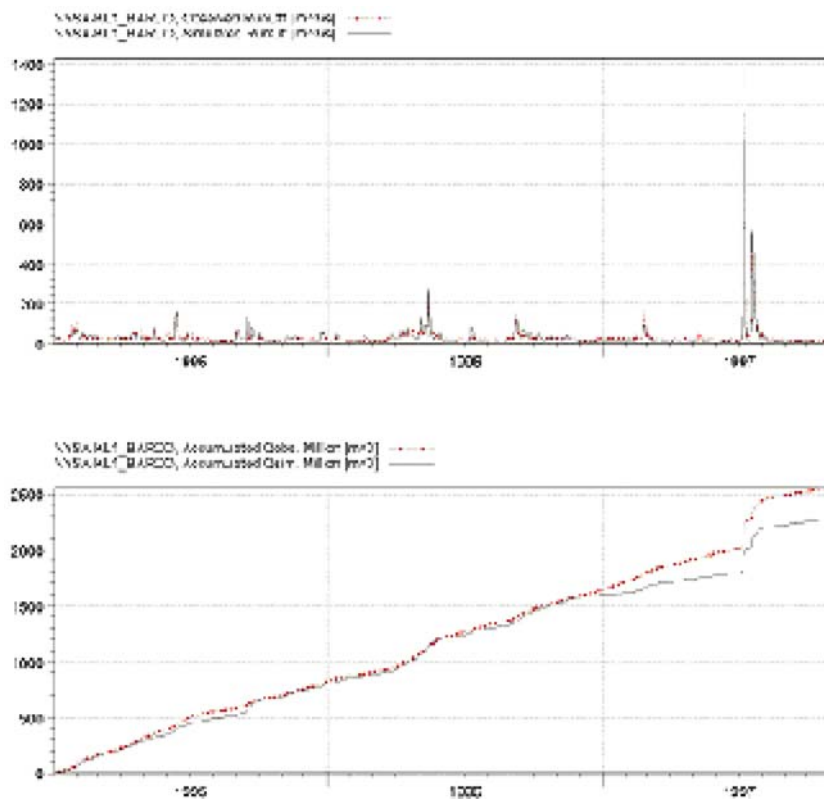


Figure 5. Measured (symbols) and simulated (line) discharge hydrograph and accumulated water balance I-runoff model for the calibration period for the Bardo station on the Nyska Kłodzka River

summary statistics of the model performance for the calibration subcatchments. The NAM model produces flow simulations of acceptable efficiency (Nash-Sutcliffe $R^2 > 0.5$) in all cases in the calibration period. From these results it was concluded that the resulting model could be used in operational forecasting.

The post-audit led to a number of observations that can be used to further improve the accuracy of the operational model. In validation period acceptable efficiency ($R^2 > 0.5$) is achieved in most cases with a few notable exceptions in the Osoblonga, Slezka and Kaczawa subcatchments. For the Osoblonga catchment, discrepancies in the mass balances for both the calibration and validation are observed and the Nash-Sutcliffe coefficient is very low in the validation period. This subcatchment contains weirs (2) and more importantly a reservoir which is not represented explicitly in this tributary in the operational model. Long-term storage effects from the reservoir may not be captured. As a result the model tends to over-estimate the low flows and also to over-estimate the actual runoff.

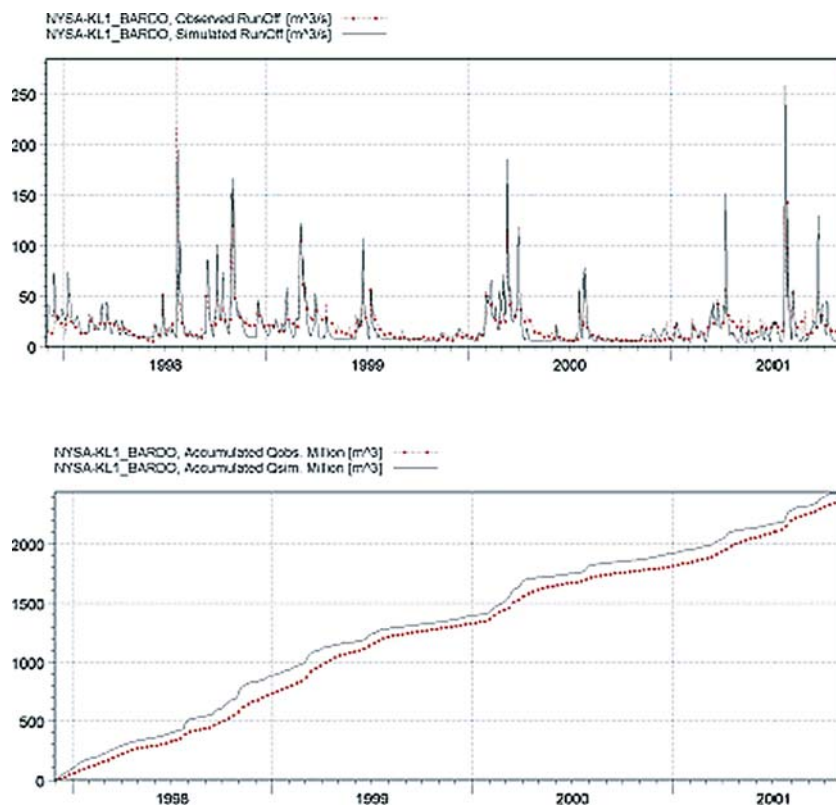


Figure 6. Measured (symbols) and simulated (line) discharge hydrograph and accumulated water balance for the validation period for the Bardo station on the Nysa Klodzka River

Similar remarks apply to the Kaczawa and Bystrzyca subcatchments, where artificial influences in the form of weirs, reservoirs and hydropower stations that regulate flows are not treated explicitly for the operational model. For the Osobloga, Klodnica and Olza catchments the application of the Racibórz station in the validation period leads to over-estimation of the subcatchment runoff in the validation period. Comparison of the annual evapotranspiration for the Racibórz and Bielsko-Biala for 1995–1997 shows annual differences of between 5–15%, which may explain the water balance errors and much of the reduced performance for these subcatchments. Flows in the Sleza and Kaczawa subcatchments are affected by water diversions and it appears that these may need to be represented in the operational model as the resulting discrepancy in water balances are significant after 1997.

The main conclusion from the post-audit analysis is that in some cases the simplifications in the representation of reservoirs, diversions and other artificial

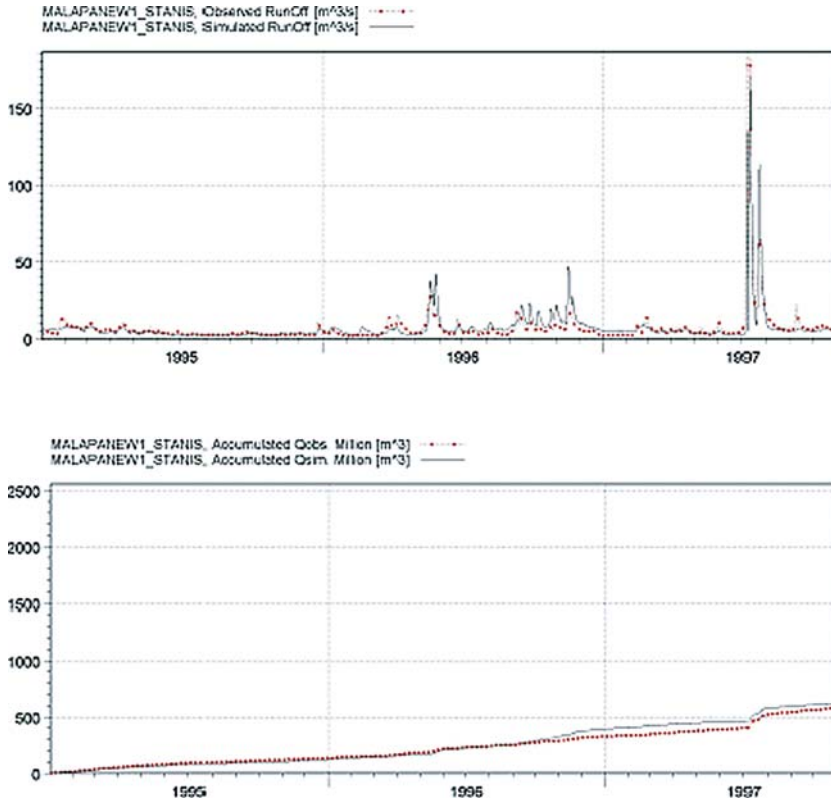


Figure 7. Measured (symbols) and simulated (line) discharge hydrograph and accumulated water balance for the calibration period for the Staniszcze station on the upper Mala Panew River

influences require revision to achieve better performance in the validation period. In the calibration period, the flows are either relatively low or extremely high (during the 1997 flood). In the validation period, a number of intermediate size events occur not seen in the calibration period. It may therefore be sufficient to re-calibrate the model over a longer period so that the rainfall-runoff calibration captures these intermediate events. However explicit representation of these influences will provide a more reliable basis for flood forecasting. The loss of the Bielsko-Bala station and replacement by the Racibórz station substantially affects the water balance and model performance in the validation period. The actual evapotranspiration in the affected subcatchments is very close to reference potential evapotranspiration, which suggests that this station may not be representative and the reference evapotranspiration is under-estimated, Table 2. Both these issues will be addressed in future work.

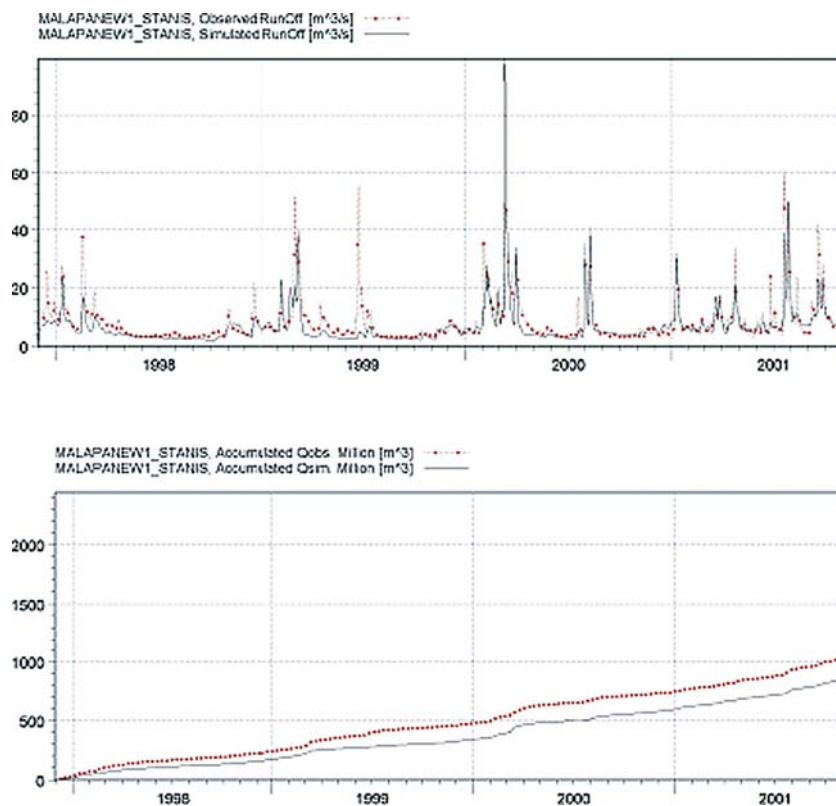


Figure 8. Measured (symbols) and simulated (line) discharge hydrograph and accumulated water balance for the validation period for the Staniszcze station on the upper Mala Panew River

4.2. The River Network (Hydrodynamic) Model

The river system described in the model covers 510 km of the upper and middle Odra starting from the Czech border (at Chalupki) and ending close to the German border (at Polecko). In addition the model includes the downstream sections of the 14 most important tributaries, (Figure 2).

The modelled river network for the Odra River and its tributaries was taken from the GIS coverage supplied by Regional Water Management Board, Wroclaw. In addition, a series of 1:50000 maps showing the extent of the 1997 flood have been used to prepare floodplain flow branches. Figure 2 shows, as an example, the model set-up for the area surrounding the town of Wroclaw. Cross sections for the Odra River were obtained from the IMGW (Wroclaw) and Regional Water Board in Wroclaw. Cross section spacing is generally around 1000 m except within Wroclaw city where the cross section spacing is typically 300–500 m. The measured cross sections often extend beyond river embankments and were used to define the floodplain geometry.

Table 3. Simulation statistics for the rainfall runoff subcatchments for the calibration and the validation period. The table shows the catchment area, Nash-Sutcliffe efficiency (R^2) and water balance error (WBL) as a percentage of the observed flow (mm/year) for each calibration catchment. The water balance errors are positive when the measured flows exceed the simulated flows. The symbol '**' indicates stations where a significant period of the measurement is missing

River	Station name	No	Catchment Area (km ²)	Calibration (1995–1997)		Validation (1998–2001)	
				R^2	WBL (%)	R^2	WBL (%)
Olza	Cieszyn	1122	453	0.90	+1	0.62	–25
Kłodnica	Lenarowice	1204	1086	0.56	0	0.58	–29
Osobloga	Raclawice	1231	498	0.81	–19	0.25	–37
Mala Panew Upper	Staniszczce	1303	1107	0.85	–1	0.61	+17
Nysa Kłodzka Lower	Bardo	2103	1744	0.88	+9	0.59	–3
Olawa	Olawa	2201	957	0.66	–5	0.61	+17
Sleza	Borow	2301	547	0.75	0	0.33	+22
Widawa Upper	Zbytowa	2501	721	0.54	0	0.80	–5
Widawa Lower	Krzyżanowice	2502	1424	0.67	–3	0.81	+8
Bystrzyca	Jarnoltow	2404	1710	0.88	+1	0.51	+40
Kaczawa	Piatnica	2603	1820	0.83*	0*	0.38	–14
Barycz	Osetno	2703	4573	0.68	0	0.77	–11
Czerna	Zagan	2891	896	0.51	–2	0.83	–26
Bobr	Jelena Gora	2806	1049	0.82	–1	0.69	+7

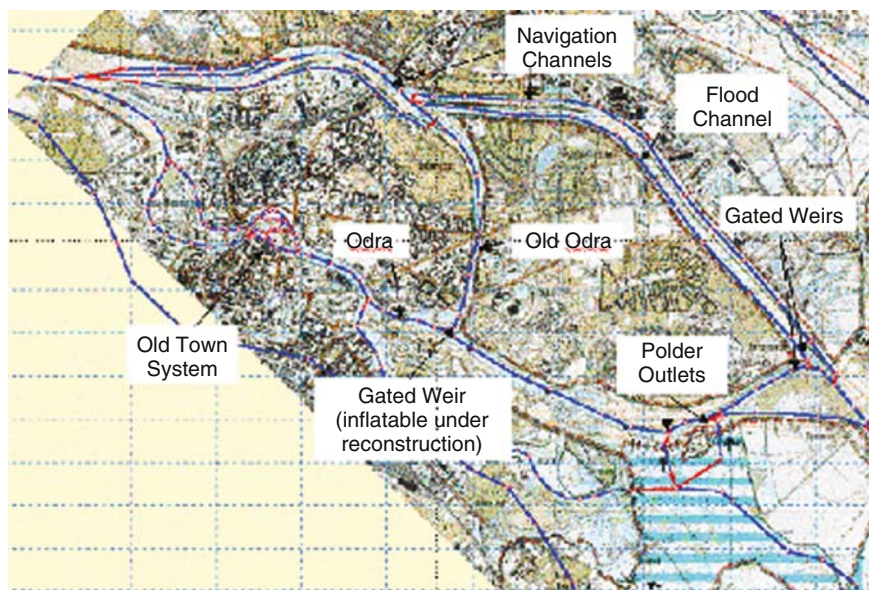


Figure 9. The river network representation on the Odra River model for the Wrocław Water System

The Odra River is maintained as a navigable river from the mouth upstream as far as Kozle. Therefore a large number of sluice and lock structures have been constructed on the river. In addition, many of the towns along the river have constructed flood defence works in the form of bypass and diversion channels. A small number of run-of-river hydroelectric plants have also been constructed in a number of places, such as Wroclaw, Brzeg and Brzeg Dolny. Navigation structures typically comprise a lock located alongside a gated structure with the aim of maintaining a given navigation depth upstream to within a 50 cm interval. Figure 10 shows a typical structure at Opatowice, upstream of Wroclaw. The retractable segment gate is lowered into the structure foundation during high flows in the river. All of the important structures have been included in the model. A total of 30 structures are modelled as moveable control structures, which are operated for navigation during low flows, with special rules being applied during flood periods.

4.3. Polders and Floodplains

Along the Odra River floodplain a number of low lying areas or polders are used as active flood mitigation reservoirs during higher river flows. These areas are generally embanked and incorporate a mixture of both fixed and moveable inlet and outlet structures, which are operated according to a predefined set of rules. Figure 11 shows the inlet structure of a polder near Trestno. The 10 most important polders and associated structures are included in the model set-up.

Flood embankments along many reaches of the Odra River protect flood-prone areas from inundation during moderate flood events. During major floods, such as those that occurred in 1997, these embankments may be overtopped, bypassed or breached. This leads to the situation where the water level on the floodplain outside



Figure 10. The moveable gate structure at Opatowice upstream of the town of Wroclaw



Figure 11. The inlet sluice structure for the polder near Trestno close to Wrocław

the embankments differs from the water level in the river. In order to model this phenomenon accurately, the floodplain flow paths needed to be included in the model as separate channels running parallel to the main river in a similar manner to those shown in Figure 9.

Where no other information was available, floodplain levels were extracted from spot levels on 1:50000 maps of the river basin. The extent of the floodplain was estimated from these maps. These floodplain areas were then compared to the extent of the 1997 flood, which had been mapped following the event, as a check that these include the observed flooded area during 1997. The floodplains are joined to the river by link channels. These simulate the flow over the river embankments and onto the floodplain. Link channels have generally been located where local depressions in the longitudinal profile of the embankments are evident. The bed level of the link channel has been set to the embankment level at these points. The link channel widths are generally subject to calibration. These are adjusted to represent the out of channel flows by examining the behaviour of the flood wave, both flows and water levels as it propagates through the main channel system. Where the floodplain channel terminates, low level, narrow link channels connect the floodplain back to the river. These simulate drainage structures, pumps, etc., which would be used to drain water from behind the embankments in times of overtopping and excessive local rainfall runoff. The bottom level of these draining links has been set to the bed level of the floodplain to ensure total drainage of the floodplain.

The three most important reservoirs have been included in the model. These are Nysa and Otmuchow on the Nysa Kłodzka River and Turawa on the Mała Panew River. The model incorporates the main flow control structures of these reservoirs including their operating rules.

4.4. Calibration and Validation of the Hydrodynamic Model

The most important variable for predicting the impact of a flood event is the water level. The river water level determines whether the floodplain area surrounding the river will be protected by the embankments or not and also determines the functioning of many of the control structures and reservoirs. Furthermore the major flood in 1997 exceeded all previous records on many gauges along the river. Streamflow gauging was not practicable during this disaster and therefore rating curves had to be extrapolated to estimate peak flows. For these reasons, the calibration of the river hydrodynamic model focussed on predicting water levels particularly during the high flows and correctly representing the propagation of flood waves through the main river system. Both the measured water levels and flows were used in the calibration, but for the extreme flows more reliance was placed on the measured water levels than on the flows derived from these water levels.

A manual procedure, described earlier, was used in the calibration of the river channel and floodplain system. The model has been calibrated at 14 important water level stations with additional data from two other stations during the 1997 peak. The stations used are listed in Table 4 in order from upstream to downstream, together with the corresponding river chainage. During the 1997 flood many of the embankments protecting properties on the Odra floodplain were breached, making exact calibration of this event more difficult.

During the calibration it was found that the flows on the floodplain played a major role in the progression of the 1997 flood, including flows into and out of the

Table 4. Water level stations and their river chainage (m) used for the calibration of the river hydrodynamic model for the upper and middle Odra

Water level station	River chainage (m)
Krzyzanowice	33550
Miedonia	55530
Kozle	97200
Krapkowice	124600
Opole	152254
Ujscie Nysy	180600
Brzeg	199000
Olawa	216500
Trestno	242090
Brzeg Dolny	284700
Malczyce	304740
Scinawa	332040
Glogow	392900
Nowa Sol	429743
Cigacice	471300
Cigacice	491500

larger polders. Hence the link channels which control the flow between river and floodplain were adjusted iteratively until the best agreement between simulated and observed water levels on the river was obtained. Some inconsistencies exist in the area upstream of Wrocław, where it is evident that the floodplain levels obtained from the topographical maps do not provide sufficient accuracy to allow a better calibration in this area. In addition, some cross sections used in the model date from surveys undertaken 20–30 years ago. Despite these difficulties good calibration results were obtained in many stations, particularly in the upstream areas.

A comparison of the measured and simulated water levels through the main river system is shown for the calibration period in Figure 12 to Figure 15. These figures show the water levels progressively down through the main river system. There appears to be satisfactory agreement between the model simulations and the observed water levels for the calibration period and in particular for the 1997 peaks. In some cases, the initial water levels are set too high but this only affects the first few weeks of the calibration. For the peak flows, the operation of many of the structures along the river will have little impact as these were left open to allow effective transport of the flood wave. For the lesser flows, many of the structure settings were not recorded and these unknown settings may be responsible for the deviations seen for these smaller flows. It was concluded following the calibration of the upper and middle Odra shown here that the model would be suitable for flood forecasting especially if combined with real-time updating or data assimilation.

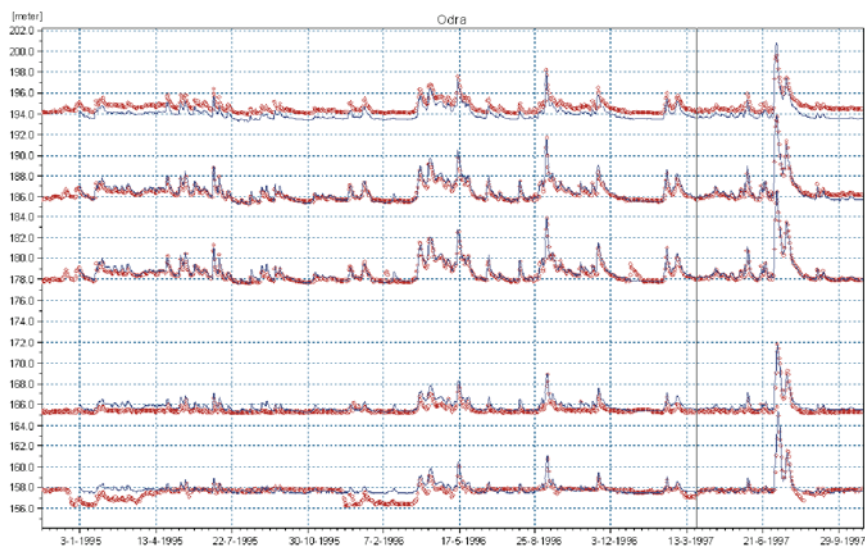


Figure 12. Comparison of the measured (symbols) and simulated (line) water levels for the calibration period, 1995–1997

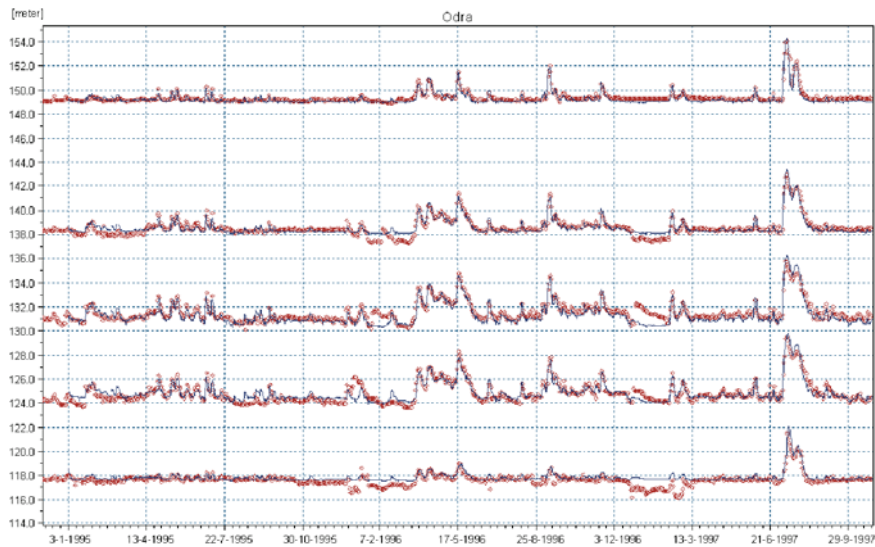


Figure 13. Comparison of the measured (symbols) and simulated (line) water levels for the calibration period, 1995–1997

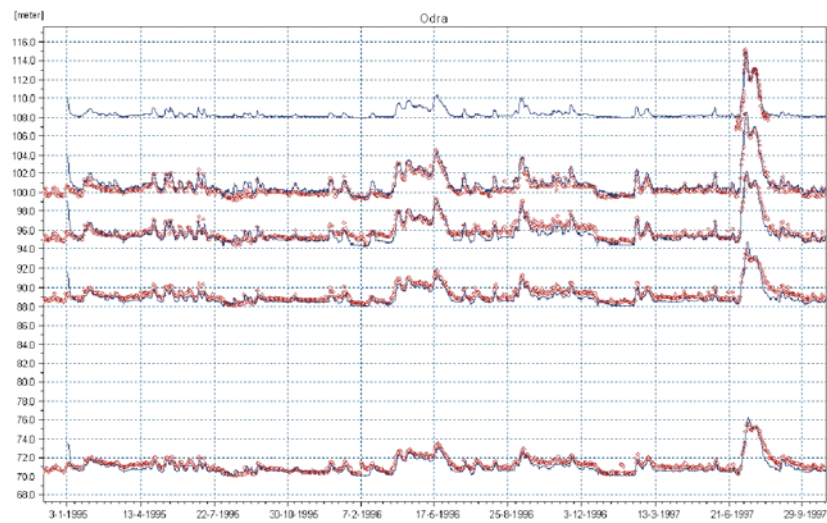


Figure 14. Comparison of the measured (symbols) and simulated (line) water levels for the calibration period, 1995–1997

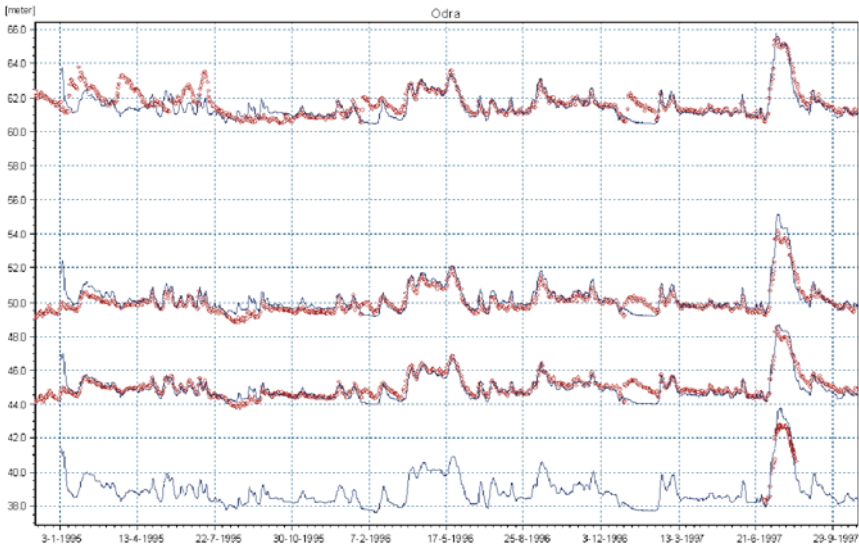


Figure 15. Comparison of the measured (symbols) and simulated (line) water levels for the calibration period, 1995–1997

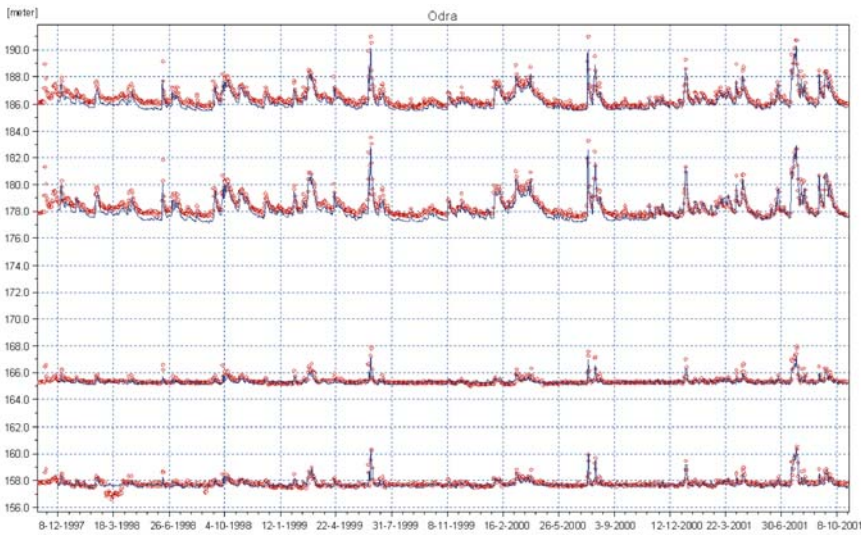


Figure 16. Comparison of the measured (symbols) and simulated (line) water levels for the validation period, 1998–2001

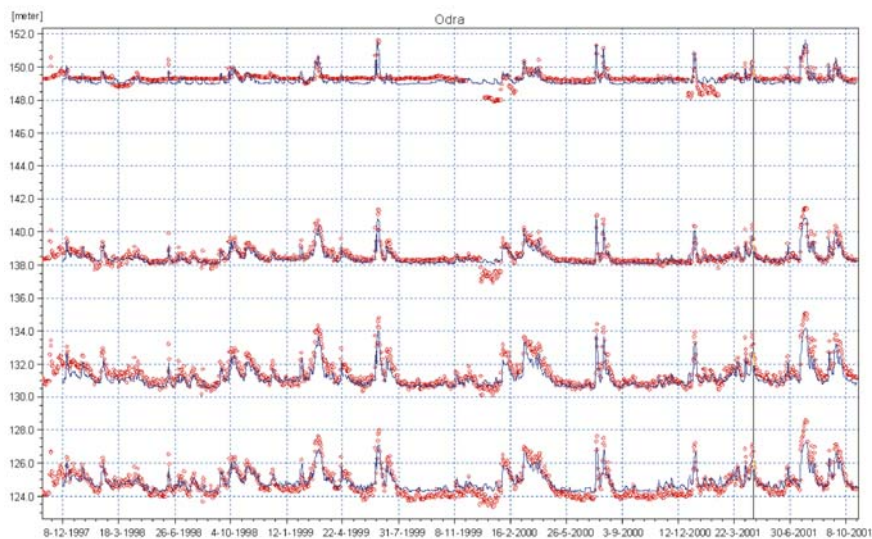


Figure 17. Comparison of the measured (symbols) and simulated (line) water levels for the validation period, 1998–2001

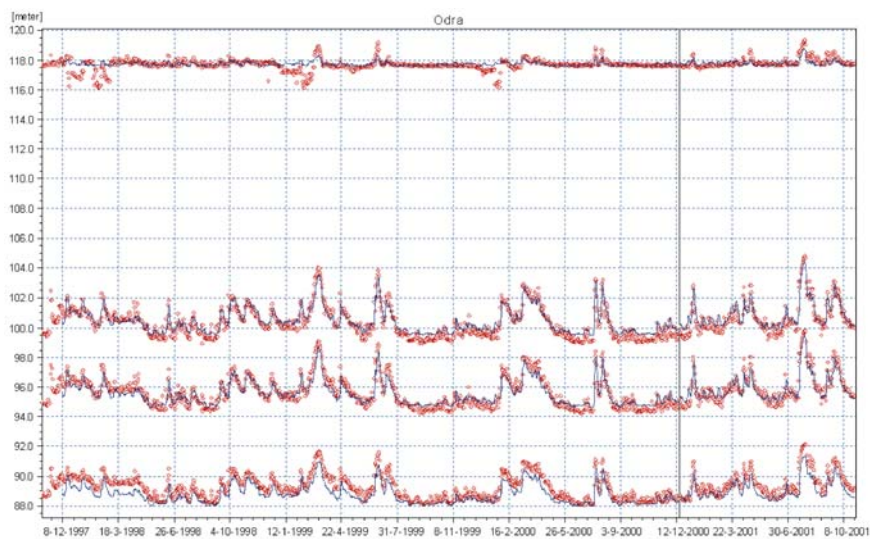


Figure 18. Comparison of the measured (symbols) and simulated (line) water levels for the validation period, 1998–2001

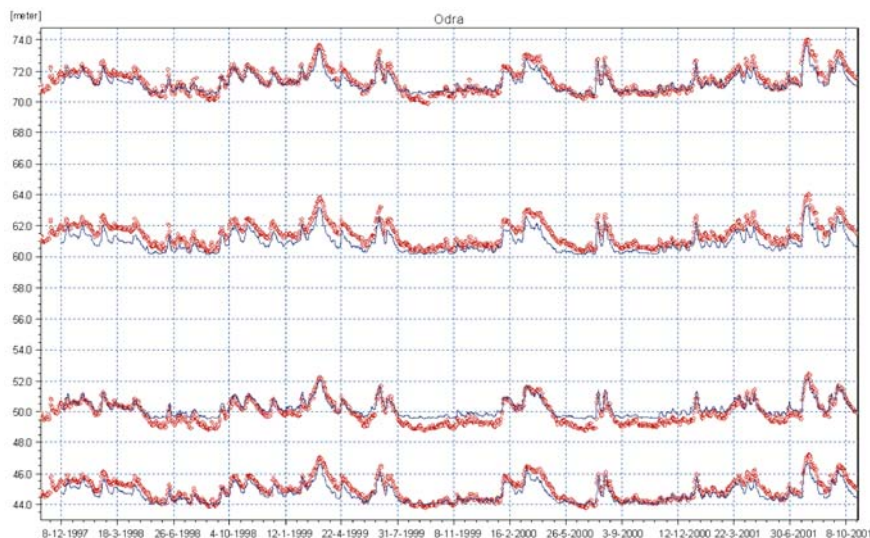


Figure 19. Comparison of the measured (symbols) and simulated (line) water levels for the validation period, 1998–2001

Following the 1997 flood event, major changes to the river system have occurred either directly as a result of the flood damage or as a result of subsequent reconstruction and new flood protection works. In order to model the river system and in particular the water levels in the Odra after July 1997, a number of alterations to the model had to be made to include new channels, new cross-sections and embankments and new structures. After these modifications were carried out the model was run for the validation period and the results are shown in Figure 16 to Figure 19. The overall agreement between the observed and simulated water levels in the river channel is satisfactory. It should be noted that measured boundary conditions were used for the hydrodynamic calibration and validation so these results are independent of the performance of the rainfall-runoff calibration in the tributary catchments. A general tendency to underestimate peak water levels in the middle section of the main river was found. Further refinement of the post 1997 river model may be possible in this section of the river.

5. IMPLEMENTATION OF FLOOD FORECASTING AND MANAGEMENT SYSTEM FOR REAL TIME OPERATION

The purpose of flood forecast modelling is to provide managers and operational staff with forecast information that allows them to make management decisions efficiently during a flood event. This requires capture of real-time information for flood monitoring, and for flood forecast modelling, provision of timely and accurate flood forecasts and well-organised, easily understood and highly visual forecast

information for decision making. This section describes the implementation of the MIKE 11 model of the upper and middle Odra in a real-time flood forecasting and management system, which integrates these various needs. The real-time decision support system for flood forecasting was established in Wroclaw based on the MIKE FLOOD WATCH system (Jørgensen and Høst-Madsen, 1997). The main components of the system are real-time databases, flood forecasting models, in this case the river and catchment modelling tool MIKE 11 including the flood forecasting module and a graphical user interface based on the ArcView Geographical Information System (GIS).

The integration of a flood forecasting system into a GIS environment provides a very powerful tool for decision making for real-time flood forecasting and flood warning. Once the database is established and the graphical display of stations configured, the system allows for the fast and easy handling of the procedures involved in the management of a real-time flood forecasting and warning system. The system can run in a fully automatic mode by means of a built-in task scheduler, or in a manual mode, where the operator controls the system.

5.1. Real-Time Data Management

The flow of data within the flood forecasting system is sketched in Figure 20. Hydro-meteorological data is imported to MIKE FLOOD WATCH databases from the operational telemetry databases through a data conversion module. Import of data can be run automatically or manually. Quantitative forecasts of precipitation, and inflow to upstream boundaries in the forecasting period can be imported by

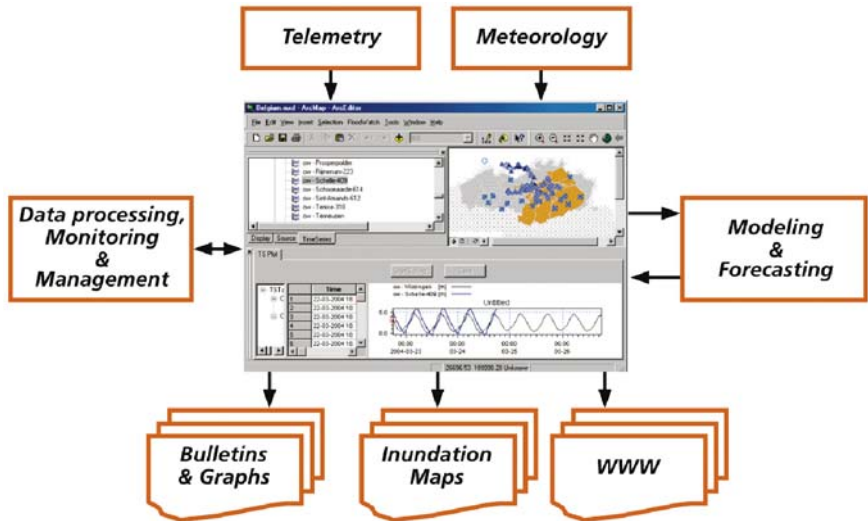


Figure 20. A schematic outline of the data flow in the MIKE FLOOD WATCH forecasting system

means of the data entry module. Before calculating a forecast, some processing of the input data is generally required. This is carried out automatically and includes interpolation of input data, consistency checks, gap filling and transformations such as rating curve relations or unit conversions.

Once a request for a forecast is made, either manually or via the task scheduler, the system will automatically extract the required data for use in the forecast model. The model simulation is then automatically executed and the forecasts are transferred back to the MIKE FLOOD WATCH database for display and further dissemination. The graphical display in ArcView is automatically updated with the most recent flood information. In addition, forecasts can be produced as graphs of measured and forecasted water levels and discharges, as printed bulletins or saved in HTML format for display on an Intranet or the Internet.

5.2. The GIS User Interface

As the first step in establishing the system on the Odra River, various thematic maps were collected for use in the graphical display. These include, the topography, the locations of rivers, catchments and reservoirs, cities and national boundaries. Using the historical and real-time data within the database, displays can be made of the water level, discharge, rainfall, temperature and snow cover by station or maps of rainfall, temperature and snow cover. A station status allows the operational forecaster to make a rapid assessment of the actual catchment conditions during an event, (Figure 21).

Configuration tools are provided to define data streams to be used and produced during a forecast. This includes the telemetric stations that are imported, stations where boundary estimates are specified for forecast simulations, real time stations to be included in the forecast simulation, a predefined forecast bulletin, the forecast stations to be shown in graphs and a predefined layout within ArcView for display on the Internet. After having established the flow of data within the MIKE FLOOD WATCH system, all real time data can be automatically imported, presented in tables, graphs or maps as required. Manual forecasts can be prepared quickly in a user-friendly environment. A forecast can generally be issued within minutes as all necessary data management tasks are carried out automatically.

5.3. Flood Forecasting and Updating

The demand for accurate flood forecasts is motivated by the fact that both human lives and property are at risk during a major flood. Therefore a key requirement to ensure the accuracy of operational forecasting using hydrological and hydrodynamic models is the need for forecast updating. Updating or data assimilation refers to methods that take into account measurements of water level or discharge in preparing a forecast, adjusting through a feedback process the model to match the observations. Updating is adopted for real-time forecasting to improve the initial state of the system prior to the time of forecast. Furthermore, updating is applied

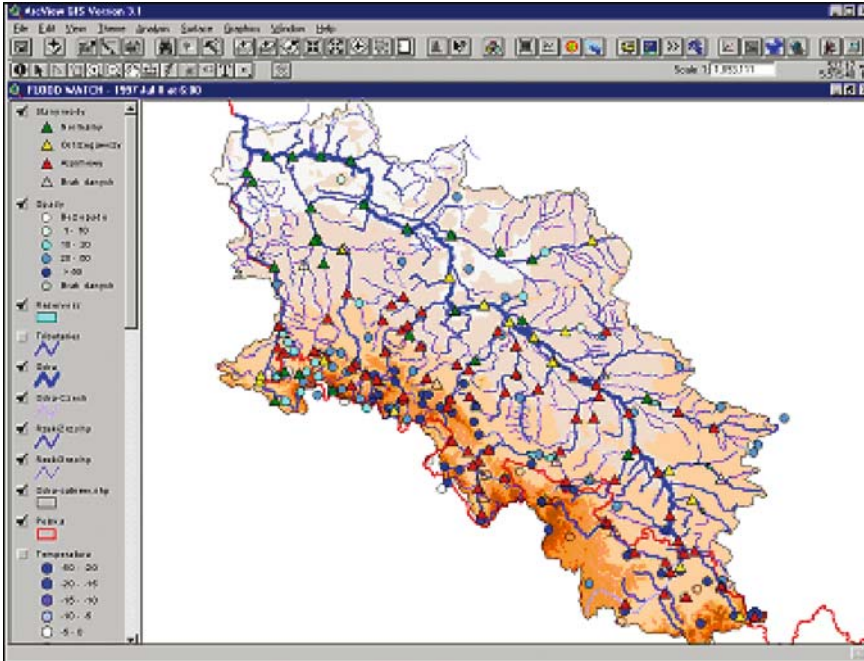


Figure 21. Flood Status map for the upper and middle Odra River for 8 July 1997. The water level status at the gauging stations is shown as a coloured triangle, red for alarm levels, yellow for warning levels and green for normal levels. The rainfall stations are shown as blue filled circles, where the darkest blue indicates more than 50 mm rainfall during the last 24 hours

to model correction in the forecast period to account for any inadequacy in the model or in the input data. Updating the forecasts on observed streamflow or water levels provides a practical method of reducing the sensitivity of the flow forecasting model to uncertainties in rainfall data as well as taking advantage of the persistence in hydrologic flows to reduce prediction errors, (Butts et al., 2002). In the WMO hydrological modelling intercomparison study one of the main conclusions was that updating should be a requirement for flood forecast modelling (WMO, 1992). MIKE 11 includes methods that adaptively use real-time observations for forecast updating within the flood forecasting module, (Rungø et al. (1989).

6. SUMMARY AND CONCLUSIONS

Flood forecasting within the upper and middle Odra provides a challenging modelling problem. The main river system is a complex river network with numerous fixed and moveable hydraulic structures, several reservoirs and 14 flood storage reservoirs or polders. Accurate flood forecasting requires comprehensive modelling of the river and channel system, flood plains, polder subsystems,

reservoir, structures as well as the rainfall-runoff processes including snows melt in the tributary catchments. However, operational forecasting also requires both fast and accurate models and therefore a trade-off must often be made between speed and complexity.

This paper describes the development, calibration and validation of a distributed hydrological and hydrodynamic model based on the MIKE 11 river and catchment, modelling tool. The development and calibration of this model was originally motivated by the need to provide operational flood forecasting for the upper and middle Odra in response to the 1997 flood. In addition, this model forms the reference case for a more general investigation into hydrological simulation accuracy and uncertainty with the EU project FLOODRELIEF. Uncertainty in the model structure, model parameters and rainfall estimates which constitute the main inputs to the models are significant sources of uncertainty that affect the accuracy of distributed hydrological models for water resource management and flood forecasting. Within the FLOODRELIEF project, the Odra basin was identified as a study basin in which different distributed modelling approaches are being developed to explore what improvements can be achieved using alternative distributed modelling approaches.

An evaluation of the performance of the MIKE 11 model is carried out using a split sample strategy, where the model is first calibrated and then evaluated against an independent validation period. The performance is presented in the form of summary statistics, water balances and flow and water level hydrographs. A strict two-step calibration procedure was applied. Firstly, the upstream rainfall-runoff subcatchments were calibrated against observed flows using an automatic calibration procedure. In the second step, the parameters for the river and floodplain hydrodynamic model and the rainfall-runoff models for the riparian subcatchments were calibrated manually following an iterative procedure. This evaluation shows that the MIKE 11 model reproduces well both the tributary inflows to the Odra River and the water levels within the main river. In particular, the tributary peaks and the propagation of the flood wave through the river system during the 1997 flood are well represented. These results confirm the suitability of this distributed model representation for operational flood forecasting. The subsequent implementation of this model in a GIS-based flood forecasting system, MIKE FLOODWATCH is described with reference to the requirements for modelling in an operational environment.

Also within the FLOODRELIEF project, a general hydrological modelling framework has been developed for hydrological modelling and flood forecasting. This framework allows alternative model structures to be used and evaluated. (Butts et al., 2004). The ability of these alternative process descriptions to accurately represent the complexity of catchments like the Odra will be evaluated against the operational model developed here. The results of this study demonstrate that this operational model is a suitable reference for our investigations of simulation uncertainty using distributed models.

The FLOODRELIEF project has provided an interesting opportunity to use the model validation analysis to carry out a model post-audit. Several findings from this analysis can be used to further improve the operational model. Some refinement of the hydrodynamic description of the main river channel following the reconstruction that occurred as a result the 1997 may be beneficial. In some cases, the assumptions and simplified representations of reservoirs, diversions and other artificial influences in the rainfall-runoff models, which were satisfactory for the calibration, will require revision to achieve better performance in the validation period. The rainfall-runoff results for the uppermost tributary catchments were sensitive to stations used and alternative more representative stations should be examined. This type of post-audit analysis is extremely valuable in evaluating model performance and ensuring continuing improvement in flood forecasting accuracy.

Future work in the FLOODRELIEF project will examine the performance of distributed models in forecast situations and where these models are driven by distributed rainfall forecasts, the associated uncertainty in the hydrological forecasts. Methods for dynamical downscaling based on nesting of non-hydrostatic numerical weather prediction models are being explored to determine what improvement in quantitative precipitation forecasting can be achieved using this approach.

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CHAPTER 20

FLOOD FORECASTING IN THE ANGLIAN REGION

User-driven Development towards Forecasting Flood Risk

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Abstract: The Anglian Region of the Environment Agency of England and Wales has replaced a fragmented and in most places technically limited flood forecasting capability with a state of the art system (the Anglian Flow Forecast and Modelling System – AFFMS). This has created a platform from which to tackle issues of accuracy, reliability and timeliness and has expanded access to forecasts to a wide customer base. Perhaps most importantly, it will help flood event managers move from a relatively passive (monitoring) mindset, to a forecasting approach that considers “what will, or what might happen?” However, the demands upon flood forecasting are increasing beyond even this newly acquired capability

This paper reviews the technical and organisational improvements achieved in the Anglian Region within the context of the traditional structure of forecast delivery. It then considers future challenges, proposing a development of this structure to a probabilistic or risk-based approach. This approach explicitly incorporates the limitations inherent in predicting flood events due to the natural variability and inherent uncertainty of hydrological systems. It develops the proactive forecasting mindset further to consider “how likely is a particular outcome?” and “what are the likely consequences?” It also provides a framework within which technical developments can be prioritised and expectations managed

Although the specific circumstances of Anglian Region are unlikely to recur elsewhere, it seems likely that the need for risk forecasting will emerge elsewhere, at least within service-orientated societies. The paper therefore concludes that, if forecast delivery is to keep pace with rising demands, highest priority should be given to coupling probabilistic forecasting with forecasting the depth and velocity of inundation. This will require advances in forecasting science

The views presented in this paper are those of the authors and not necessarily those of the Environment Agency. They should not be taken to represent the policy of the Environment Agency.

Keywords: Anglian Flow Forecasting and Modelling System, flood forecasting, end-user requirements, uncertainty, risk-based flood management, probabilistic forecasting

1. FORECASTING IN FLOOD EVENT MANAGEMENT

1.1. The Challenge to Flood Forecasting

Flood events are generally managed by continuously monitoring waterbodies and assessing their potential for flooding in real-time. Where flooding is likely, those potentially affected (the public and businesses), and those protecting them (emergency services and local government) are warned, and warning recipients then act to reduce losses. This is typically represented as a process (Figure 1) with component activities of Detection, Forecasting, Warning and Response (Handmer et al., 1997).

Though warnings trigger action by recipients, flood warning is essentially an information management problem - producing knowledge about how to respond to a situation from the data detected. The process structure organises this into a chain of information supply and a series of customer-supplier relationships in which the end users – warning recipients - drive the needs of each stage.

Information supply is separated into off-line and on-line (real-time) components (Figure 1) because the time available to impart information during a flood event is typically very limited. Off-line information resolves (as far as possible) social, economic, political and technical aspects of flood management into a set of pre-determined actions that simplify decision-making in real-time. This is achieved with emergency services and warning disseminators through agreed emergency plans, and with warning recipients through awareness campaigns. Real-time communication, which includes forecasting, then triggers the use of this pre-prepared information as a flood event develops.

The challenge to the off-line component of information provision is to ensure receipt of warnings, to ensure recipients know how to mitigate damage once they are received, and to simplify a potentially complex decision of whether to warn to a forecasting judgement about whether predetermined conditions will be met. The challenge for the real-time component is to deliver warnings to the right people, in time for them to respond effectively, every time they are at risk, and yet to



Figure 1. Flood warning as a process

avoid false alarms. This challenge is conveyed to forecasters by flood warning practitioners: Provide forecasts that anticipate flooding accurately, reliably and with sufficient lead-time.

1.2. Meeting the Challenge

There is no single best means of anticipating flooding accurately, reliably and with sufficient lead-time. Rather, there are a variety of approaches and each offers a different combination of accuracy, reliability and timeliness in any given situation. Warnings can be triggered either by forecasts or by observations reaching pre-set states (triggers). Triggers can be applied to different variables singly or in combination (e.g. conditional relationships). They make no explicit forecast of the outcome of an event, but can perform well in relatively simple situations. There are also numerous means of forecasting. Forecasts are better able to filter out false alarms, but they cannot be perfectly accurate, so to do so they must allow some possibility that a flood will not be forecast.

Selecting the best approach requires a series of trade-offs. The improved response gained from reducing false alarms must be traded-off with the potential risk of failure to warn of flooding. Reducing forecast uncertainty can limit the degree of compromise in this trade off, but cannot eliminate it. Moreover, as forecast uncertainty is reduced through investment, this introduces a trade-off between investment and the risk of failure (Khatibi et al., 2002). Finally, for any given investment, the greater gain in lead-time that is sought, the greater the forecast uncertainty becomes (Butts et al., 2002), so introducing further trade-off between timeliness and accuracy. In theory these trade-offs could be optimised, but in complex situations, operational practice is more usually based upon engineering judgement, often deploying forecasts with triggers set as a precautionary failsafe.

2. THE ANGLIAN REGION: RECENT CHALLENGES AND SOLUTIONS

2.1. Modelling Challenges

The catchments and river systems of the Anglian Region of the UK are varied, complex and prone to flooding (Figure 2). Fluvial flooding is typically caused by frontal rainfall onto saturated soils during winter, but snowmelt, infiltration rate excess and groundwater have all had significant impacts. Small clay headwater catchments on the western edge of the Region create rapid run-off, yet elsewhere flow exchanges are complicated by groundwater interactions with chalk, limestone or glacial drift deposits. There are also long stretches of low gradient river channel, which are affected to a very substantial degree by water extraction, effluent inputs and impoundment for navigation or flood defence. The extent of artificial control reaches an extreme in the Fens. Here, flat catchments are sub-irrigated in summer and drained by pumps in winter, and tidal sluices control the embanked rivers at their downstream ends.

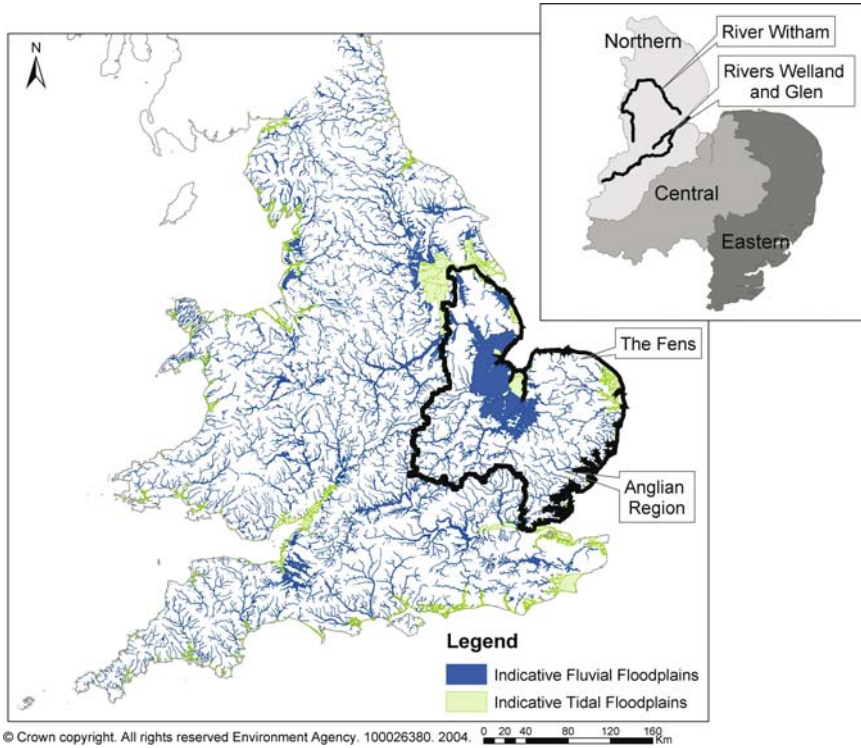


Figure 2. Flooding in the UK, with detail of the Anglian Region

Significant investment in forecasting is justified in the Anglian Region to mitigate flooding, and because forecasts can be used across the range of flows to control water extraction and to operate water transfers, environmental mitigation schemes and navigation structures. Significant investment is also needed to cope with the Region's complexity.

2.2. Technical and Organisational Forecasting Capability in the 1990's

Until the early 1990's, the comprehensive solutions required could not be combined with rapid information assessment across large areas in an operational forecasting system. This limited the likely success of forecasting investment in Anglian Region, a disincentive reinforced by a long-established cultural preference for traditional flood defence schemes, and dislocation within the Region between the appropriate source of drive and funding (the Flood Defence function), and of forecasting delivery (the Water Resources function).

Investment in forecasting was also spread thinly. Event management was delivered as almost independent services from the Region's administrative Areas

(Figure 2) and drive, priorities, preferences, the availability of funding and of the technical and project management expertise to select and deliver solutions varied between each. As a result, the Region deployed a patchwork of forecasting approaches, often developed as static outputs from one-off projects. Triggers were widely used, forecasts less so, and not always with precautionary back up from triggers. The most widely used forecasts were empirical relationships, with limited geographical coverage from transfer function based rainfall-runoff models and from the Lincoln Flood Alleviation Model (LFAM) in Northern Area. The LFAM was arguably the most complex forecasting model in the UK at that time, using conceptual rainfall runoff and snowmelt models to feed a 1-dimensional hydrodynamic model and sluice optimisation procedure upstream of Lincoln. Forecasts from these various approaches were only inconsistently successful.

In the early 1990's, the inadequacies in this deployment of techniques and resources were in part concealed by a dearth of major flood events, and by poor warning penetration. However, they inhibited ongoing development and resource transfer between Areas and only loosely matched resource allocation to the risk of flooding. It also struggled to deal with the complexity of the Region. When used alone, triggers offered scant information for forecasters to add value to predetermined procedures, and it is also probable that their use fostered a relatively passive (monitoring) mindset rather than one of actively anticipating (forecasting) floods. This is an unconvincing basis from which to react to extremes.

Forecasts inevitably performed best where channel processes dominated and were less accurate where observed or forecast rainfall had to be used to gain lead-time. The simple relationships were successful in many locations but were less so where hydrograph shape or the behaviour of hydraulic controls varied between events. The transfer function models performed well at times but behaved erratically at others, even when assimilating small amounts of new information. This unpredictability undermined confidence amongst forecasters, and placed a heavy burden on those able to add interpretative value. As the LFAM was seldom used in real events is difficult to develop a thorough understanding of its performance. However, it demanded a lot of forecaster input, having to be run by external consultants during events.

2.3. The Anglian Flow Forecasting and Modelling System

Widespread use of comprehensive forecasting techniques within a real-time river management system became a viable prospect in the mid 1990's, when computing improvements allowed the Region to maximise the use of numerous river models that had been developed for the design of flood alleviation schemes. To achieve this, the Region concentrated investment into a strategic Regional programme to:

- Replace three Area telemetry (monitoring) tools with a single Regional system.
- Expand the hydrometric network to provide data for improved real-time models.
- Develop a regional forecasting system, to provide a common platform for fluvial forecasting for flooding, water resources, navigation and other use.
- Utilise the design models to improve forecast performance and coverage.

This programme was later further enhanced by upgrading the weather radar system.

The core of this forecasting capability is a set of comprehensive forecasting models set within a state of the art real-time forecasting and monitoring tool, the Anglian Flow Forecasting and Modelling System (AFFMS) (Butts et al., 2001). This system provides a highly resilient platform that at once concentrates hydrological interpretation and widens access to it, both in real-time and off-line. It has received highly positive feedback from users.

Within the AFFMS, observations and forecasts of meteorological data (rainfall), tidal data (tidal residuals), water level and flow are processed for use by models at scheduled times or on-demand. The forecasts of river and catchment states are generated by the models across the full range of flows, and are compared with predefined impact thresholds and collated into status reports to prioritise flood (or low flow) management actions. The forecasts, and forecast catchment status, are then presented to a wide variety of users whose access to functionality can be graded to target forecast information, guarantee the forecast approval process and prevent misuse. Forecast information can be visualised through maps, charts, tables and reports using a comprehensive and extremely intuitive web browser interface (Figure 3) which, when complemented by radar imagery, presents a clear view of operational events as they happen.

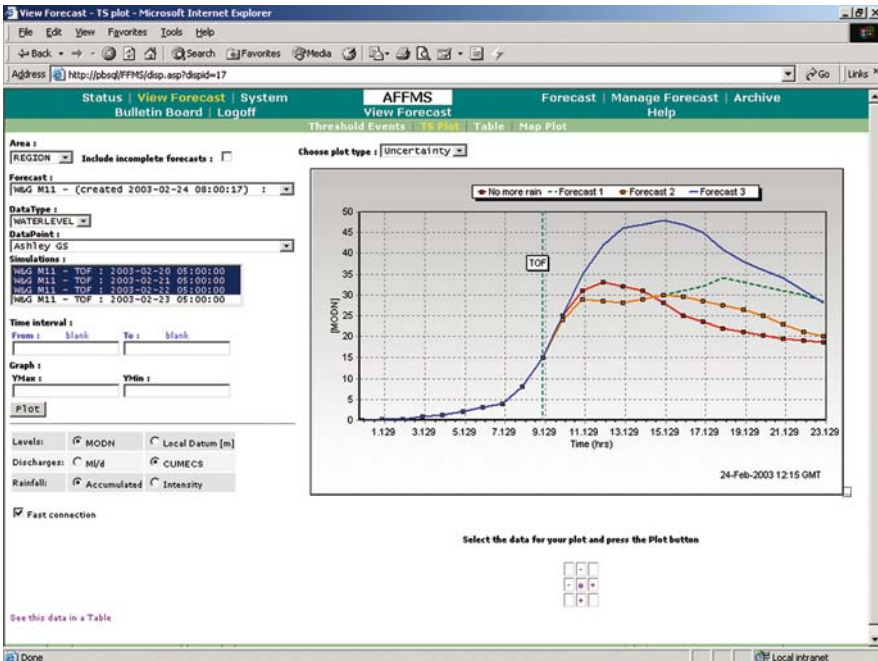


Figure 3. Scenario generation within the AFFMS

The new forecasting tools are designed with the underpinning philosophies that the forecast that matters is the forecaster's interpretation, not merely that produced by the models, and that information transfer in real-time is improved by giving wide, but controlled, access to forecasts. Model inputs are clearly displayed, and can be changed to make best use of available data. The models themselves are also thoroughly documented, detailing the simplifications and assumptions upon which the models are based. An understanding of both the physical catchment and of the models enables the forecaster to add value to model outputs by appraising the real situation against the interpretation that the model is using, and to explore the implications of data inadequacies. Perhaps most importantly, model inputs can be varied to simulate user-specified scenarios that can be compared with other forecasts (Figure 3). This allows the forecaster to explore real-time control options and unforeseen circumstances such as gate seizures, and is encouraging the forecaster to shift the use of deterministic models in real time from trying to state "what will happen" to asking "what might happen?"

Models developed for incorporation into the AFFMS are developed off-line in the standard calibration tool for whatever model is used, in a process little different from developing a model for designing a flood alleviation scheme. This facilitates the re-use of models developed for other purposes, though when models are applied as forecasting models real-time water level and flow data are also used to carry out data assimilation or updating and thereby improve the forecast accuracy (Butts et al., 2002).

The basin models form a framework around which to consolidate interpretative information about the catchment. Local knowledge has been systematically shared between disparate sources of local expertise – internal and external, hydrologists, hydro-geologists, operators, hydrometric staff and others – and this framework will be used to examine and prioritise potential improvements to the models. The limitations of instrumentalist (Bever, 2002) models based upon an a priori model structure are accepted, because this was considered the best means of obtaining an operationally useful model whilst leaving sufficient resource for modelling elsewhere.

To date two whole-basin model set-ups (Butts et al., 2001) covering the Welland and Witham catchments (Figure 1), and pre-existing simple approaches such as level to level regressions and low flow recessions have been incorporated in the AFFMS. The two basin model set-ups forecast over the full range of flows, linking conceptual rainfall run-off and snowmelt models with one-dimensional channel models. One also replicates the optimisation capability of the former LFAM. They have been developed in the MIKE 11 modelling system (Havnø et al., 1995), using the data assimilation methods developed for this system (Rungø et al., 1989). However, there are few restrictions upon the choice of modelling tool and the AFFMS has also been proven to run models developed within ISIS. This allows the Region to take advantage of market driven upgrades to other modelling tools, as well as utilise the range of approaches available within the MIKE suite.

Further models are now being developed to extend geographical coverage. Though a variety of approaches are being used, as before, the approaches are being selected within a consistent technical framework and developed to a consistent specification. The consistent technical framework, initially developed within the Region but now superseded by national guidelines (Environment Agency, 2002a) will help match investment to flood risk and the complexity of the problem. The consistent specification (currently being developed into a national specification) will ensure that the chosen solutions are developed to a common standard.

2.4. The Regional Monitoring and Forecasting Centre

Technical change was not sufficient without equivalent organisational change to parallel the consolidation of investment and technical approach with forecast delivery from a nucleus of forecasting specialists - the Regional Flood Monitoring and Forecasting Centre (RFMFC). The RFMFC was established to align the Region with major changes to national Flood Defence delivery that were provoked by significant flooding during Easter 1998 (The Bye Report, 1998). The technical forecasting recommendations had largely been anticipated in the Anglian Region (although the core capability was not deployed operationally at that time), but forecast delivery was still fragmented and dependent upon key individuals in each Area. The specialists in the RFMFC report to the Flood Defence function, but are supported during floods by a rota of trained volunteers. When they are not actively forecasting, they develop and maintain forecasting capability off-line. With this focus and technical capability, forecasts now have the potential to become a cornerstone of operational management in the Region.

3. NEW CHALLENGES AND SOLUTIONS

3.1. A New Cultural Environment

For forecasting to be considered a successful solution it will have to meet expectations that have risen substantially since the AFFMS was conceived. Flooding is now much higher on the public agenda than in the mid-1990's. There are concerns about the impact of climate change, and the impact of UK-wide flooding events in 1998 and 2000 is still being felt. Locally specific information on flood prone areas is now widely available, coming as a surprise to many, and there is reluctance by insurance companies to cover all areas at risk. Expectations of public services in general have also increased over the decade, and since the September 11th attacks in the USA, there is more scrutiny of the UK's resilience to disruptive challenges.

As a consequence of these developments, there is media coverage and political attention during events, demand for compensation when services fail and pressure from the insurance industry for loss reduction and quantitative understanding. It is also likely that the Environment Agency's responsibility for flood event

management will become a statutory duty for civil protection rather than a permissive power. The pressure for an improved service is being conveyed down the information supply chain to the forecasters via flood warning practitioners. Greater accuracy, longer lead-times, forecasts of the expected depth of flooding and spatial resolution to identify inundated areas for events of differing severity, are all now sought.

3.2. The Need for a New Approach

The greatest short-term gains in forecast accuracy can be achieved by widening the geographical coverage of models - though the forecasting platform and some models are state of the art, forecasting solutions in some places remain inappropriately crude. Forecast uncertainties at high impact sites will also be progressively targeted within the framework of the basin models until it is no longer beneficial to do so.

There is also scope to complement these incremental local improvements with medium-term developments that further increase the capability of even our most comprehensive models. In particular, the demand for forecasts of depth and velocity of inundation (which together characterise flood hazard) could be met by using 1-D, 2-D and 3-D models in real time. This would allow the Region to use 2-D descriptions of floodplain flow, as used currently for design applications (Kjelds and Rungø, 2003), and model inundation from river-estuary interaction. Though greater model complexity may not be necessary to achieve reasonable forecasts, and certainly does not guarantee them, this capability might also allow the Region to use existing aquifer models (Grout et al., 2000) to tackle groundwater flooding. However, these improvements are unlikely to be sufficient.

Generally, improvements to forecasting accuracy will be subject to the law of diminishing returns. There are also limits to the accuracy that can be achieved. Poor real time data validation and loss of data sources will limit performance at extremes of the hydrological regime, and the extremes are also intrinsically difficult to parameterise without equivalents in the measured record. There are also theoretical limits to the predictability of flood events in real time, because of the inherent chaotic variability of the underlying physical processes. The various sources of uncertainty affecting hydrological modelling for forecasting are described elsewhere; (Krzysztofowicz and Kelly (2000), Butts et al (2002)).

The difference in water level that differentiates between events of no impact (ie the river stays within bank) and very high impact (when the river overtops the bank) are often very small. We are unlikely to achieve accuracy's that would enable us to consistently distinguish between such events. This makes it inevitable that forecasters will, sometime, somewhere, fail to forecast a flood, even where they are supported by state-of-the-art models. In a deterministic environment, in which forecasters have to "make a call" as to whether a site will, or will not flood, this "wrong call" will result in the inappropriate action being taken. Caveats about the accuracy of a deterministic forecast are unlikely to prove sufficient because even fuzzy advice must, when a decision is to be made, be hardened into a single

technical recommendation - fuzzy as the statement may be, a location either floods or it doesn't!

This appears to present a fundamental problem for deterministic flood forecasting. It seems inevitable that there will continue to be pressure to improve our forecast accuracy even when we have reached the limits of our technical or financial means - even a hiatus in the absence of flood events would probably be temporary. It seems equally inevitable that, because false alarms are usually more acceptable than failure to warn of flooding, forecasters will respond to uncertainty by becoming increasingly conservative in their forecasts, leading to a higher false alarm rate and, over time, a poorer response amongst recipients.

This conjecture seems to be confirmed by experience in Anglian Region. New expectations in the Anglian Region already significantly exceed the current capability even of Anglia's state of the art models - and expectations may continue to grow faster than we can improve these models. Whilst the Region's models will not reach theoretical or even practical limits for some time, a new requirement to distinguish between a 1:10 and 1:25 year flood may require forecasting to within $\pm 150\text{mm}$ in some lowland areas. This is unlikely to be achieved at all within existing model structures with the information content of even the expanded measuring networks. Warning triggers have also been reset after Easter 1998, and, in some places where flood warnings have been issued since, warning recipients are now asking to be taken off warning databases to reduce the disruption from false alarms.

One option would be to reduce expectations by conveying technical limitations back to recipients within the deterministic framework. This could be formalised as an acceptable standard of performance for accuracy or reliability of warnings (and therefore of forecasts), defined, *a priori*, consistently, and in consultation with the public or their elected representatives. Such a standard is established practice for the design of flood alleviation schemes. It could reduce any tendency to regard uncertainty in a forecast as an unacceptable failure, and would drive the need for continued improvements to accuracy, timeliness and reliability. However, assuming the current expectations reflect genuine needs, this approach would result in genuine needs being unfulfilled. Risk management practice offers an alternative solution.

4. FLOOD WARNING AS A RISK MANAGEMENT PROBLEM

4.1. Applying a Generic Risk Structure to Flood Forecasting

Structuring flood event management explicitly as a risk problem has the advantage of accounting for inherent uncertainty in a natural way, providing a means of translating research in this area into operational practice. It also offers a means of prioritising technical development by quantifying the costs and benefits in terms of risk (Plate, 2002), and allows pressure for improvement to be more realistically and systematically applied to forecasting provision. Perhaps most importantly for the forecaster, it accepts that forecasts will sometimes be wrong, and that it is the

responsibility of event managers to manage in an uncertain environment, not of forecasters to be always correct.

In a risk management process (Figure II), detection and forecasting would form a two-part risk assessment activity, dissemination and response a two-part risk mitigation activity (Plate 1998). Judgements about how much risk is acceptable before mitigating action is taken are clearly separated from the technical assessments that inform those judgements. The role of forecasters would be to assess the risk, and that of the mitigation activity to decide whether this risk is acceptable. The decision to warn will be taken in the mitigation activity, at some point on a continuum of risk or probability of flooding. This decision could be taken on the basis of what chance of flooding recipients can accept, or at least tolerate, before action is taken, and would remain a balance between the costs of not warning of flooding and those of issuing false alarms. However, this decision would be much more explicitly related to flood impacts than would a simple standard of forecast accuracy.

The key change to forecasts is that they would be expressed as dynamic, real-time calculations of flood risk, rather than as deterministic, yes/no "calls". A probabilistic forecast is stated as a probability, for example "there is a 10% chance of flooding" of a defined area. This allows recipients to judge for themselves whether or not to take mitigating action. A forecast of risk combines this probabilistic forecast with information about consequences, stating total probable damage, and could utilise floodplain-mapping data into flood event management. This would continue the progression being achieved in the Anglian Region. From a prevalent "monitoring" mindset, deterministic forecasters now ask, "what will happen?" and this has been stretched by the AFFMS by allowing the Region to ask, "what might happen if?" A probabilistic approach would allow forecasters to ask, "how likely is it that this will happen?" and a risk forecast would allow forecasters to ask "what are the likely consequences?"

4.2. Communicating Risk Information

Probabilistic and risk forecasts do not, in themselves, improve accuracy, reliability or timeliness, but they provide information in a way that can help end-users understand the difficulties of providing accurate, timely and reliable warnings. They make it possible to distinguish between levels of certainty in these warnings such that over time recipients experience will become attuned to a graduated scale of information that is less vulnerable to the corrosive effects of issuing false alarms. These levels of certainty can also be used as a means of staged awareness raising during the build-up of a flood, allowing warning recipients to vary their level of readiness during an event as uncertainty decreases with shorter lead-times, or as the event changes.

However, communicating probability or risk information is more complicated than communicating a deterministic recommendation. A clear approach to conveying uncertainty information or simplifying it to a single recommendation

will be needed for probabilistic or risk warnings to be successful, and it may be that the information is communicated to different recipients in different ways.

Emergency services are likely to prefer a risk forecast. They would be able to combine the probable damage with a judgement of the vulnerability and sensitivity of the population at risk to prioritise sites where most damage can be averted. A member of the public may well prefer a probabilistic forecast to a risk forecast, as for an individual, the consequence of flooding is likely to be narrowly focussed and subjectively assessed. However, although the general public often intuitively understands probabilistic expressions, it may also be that they would prefer a single recommendation. Though probability information is often presented in weather forecasting in “fuzzy” terms, using expressions like “heavy rainfall may be expected”, such statements may be less useful in galvanising recipients, and will be judged against a black and white outcome at a given site. It may be that risk or probabilistic forecasts would have to be combined with “best guess” deterministic forecasts, as part of a migration to risk forecasting or as a long-term solution.

This would probably require the Environment Agency to adapt both its current warning schema and its off-line information provision. Current off-line information provision may have to inform a decision whether to respond, not simply how to. However, in an environment in which false alarms are received because of uncertain forecasts, the recipients are making this decision anyway whether our information provision acknowledges this or not.

4.3. Conclusion

Experience in the Anglian Region of the Environment Agency suggests that, appreciative of our progress as our customers are, it is unlikely that we can fully meet their expectations, even where highly comprehensive forecasting solutions have been implemented. These expectations suggest that priorities for forecasting should be for ever increasing accuracy, lead-time and reliability, and for inundation forecasting. These are worthwhile objectives in the short and even medium term, but customer-led solutions within the deterministic structure are unlikely to be longer-term solutions. Probabilistic and risk forecasting offer a more promising approach in the medium and longer term, and improvements to accuracy, timeliness and reliability may be a shorter term, lower order problem than the need to restructure forecast provision into a risk framework (Plate, 2002).

Risk forecasts are not necessarily a high priority amongst flood event managers – they are perhaps unlikely to be, given that they transfer responsibility to them from forecasters. However, it is a high priority if the flood warning process is to be successful in the longer term. Although it is important to be customer-focussed, progress in technical fields cannot be entirely customer-led. Longer-term objectives in particular often require specialist vision and an understanding of what can be achieved. In the UK, risk warnings are also consistent with overarching policy

guidance for managing environmental risks (DETR, 2000) and with a wider shift from “Flood Defence” to “Flood Risk Management” (Environment Agency, 2002b).

The biggest technical challenge to achieving probabilistic and risk forecasts is to develop tools to predict forecast uncertainty and thereafter methodologies to translate these uncertainties into risk. Success in these areas would make it relatively straightforward to calculate risk by linking the modelled river behaviour to “consequence” data, such as the flood risk maps being produced across the UK. The prediction and propagation of uncertainties has been established in operational weather forecasting since the early 1990’s (Krishnamurti et al., 1999). These use forecast ensembles (i.e. different forecasts for the same period using the same model) with estimates converted to quantitative probabilities of exceeding critical rainfall rates, rather than a single “best guess” forecast (Ehrendorfer, 1997). Ensemble forecasting is attractive as a framework for the probabilistic representation of forecasts as it allows effects of a wide range of uncertainties to be incorporated (Butts et al., 2004). Recent studies have shown the value of ensemble flow forecasting for reservoir management (Georgakakos and Krzyszofowicz, 2001) and other general methods are being developed for operational flood forecasting (Krzysztofowicz and Kelly, 2000). The idea of using multiple model simulations to evaluate the performance of different models and to identify situations where models perform well (or not) is also being actively explored (Georgakakos et al., 2004, Butts et al., 2004). To this end, the Region is actively contributing to research projects like FLOODRELIEF that are addressing these uncertainty issues (Butts et al., 2003, <http://projects.dhi.dk/floodrelief/>).

However, perhaps the biggest challenge to risk-based flood event management is to effect the necessary cultural change amongst practitioners and recipients. To move from the deterministic mindset fostered by the command and control structure to one tolerant of uncertainty (though not necessarily of error!) places more onus on forecast recipients, as it means moving from being told what to do to making decisions based upon risk. Communication of risk is also likely to be more challenging. Recipients of warnings are not specialists. They have little awareness of the underlying difficulties in forecasting and it is unsurprising if information presented as deterministic forecasts is taken as fact. In the longer-term it is possible that a greater appreciation of the nature of the risk, coupled with practical information, would enable recipients to make informed decisions in responding to warnings. It would at least do less to perpetuate a myth that we can ever deliver wholly accurate warnings.

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CHAPTER 21

FLOOD FORECASTING MODEL SELECTION

A structured approach

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Abstract: Flood forecasting models provide the capability to issue reliable warnings to the population at risk of flooding. The categories of models developed over the years range from simple empirical models to integrated catchment models combining rainfall runoff, flow routing and hydrodynamic components. This paper describes a novel structured method for selecting the most appropriate category of modelling solution to use in a given situation in the form of guidelines commissioned by the Environment Agency for England and Wales. One outcome of this approach is to provide greater consistency and auditability in the design of flood forecasting systems, and to ensure that practitioners are aware of the assumptions, limitations and likely accuracy of each approach. The resulting guideline document considers economic, operational and other factors, as well as technical factors such as catchment characteristics, and makes extensive use of checklists, flowcharts, risk assessment matrices and other techniques for guiding users through the decision making process. The guidelines are currently being used operationally and an overview is presented on experience gained in the first year since publication. A number of areas for future research and development are also highlighted which were identified during preparation of the guidelines

Keywords: flood forecasting, models, guidelines, performance monitoring, England, Wales, rainfall runoff, routing, hydrodynamic

1. INTRODUCTION

Flood forecasting models play an increasingly strategic role in the flood warning service provided by national Agencies. However, the lack of a consistent approach to model development can lead to limitations and weaknesses in the performance of the underlying system; for example, through selection of inappropriate models, or failure to adequately consider the implementation costs of a system.

Recent reviews (e.g. [Khatibi and Haywood, 2002](#); [Khatibi, 2003](#)) have also shown an emerging consensus amongst practitioners of the need for a more integrated approach to flood forecasting model development. For example, one gap which was identified was the requirement for a clear audit trail documenting the process followed in model selection, and the basis for the decisions taken. It was also noted that the confidence of practitioners in flood-forecasting based results was often low, with guidance required on approaches to monitoring and evaluation to help to identify models with poor performance.

This chapter discusses the development of a decision tree approach for the case of fluvial systems, which has the novel feature of providing a diagnostic capability encouraging an evolutionary approach to model development. The approach recognises that, in any given situation, there is no perfect model and that inevitably the idea of “horses for courses” has to be the driver for model selection. This work arose out an R&D project commissioned by the Environment Agency for England and Wales to develop guidelines for use by practitioners to determine appropriate modelling solutions, and other issues such as approaches to model performance monitoring and assessment of model uncertainty ([Environment Agency, 2002a; 2002b](#)). The overall aim was to lead to greater consistency amongst practitioners through the adoption of best practice solutions consistent with high level government targets and performance measures for flood warnings.

Perhaps the main challenge in the development of the guidelines was the need to consider the full complexity and diversity of forecasting problems which can arise, including the influences of control structures, reservoirs, lakes, flood-plains, confluences and ungauged tributaries, as well as the plethora of flood forecasting techniques which are available. Although there have been several excellent technical reviews on these topics (e.g. [Reed, 1984](#); [World Meteorological Organisation, 1992](#); [Moore, 1993](#); [British Hydrological Society, 2000](#); [Wagener et al., 2001](#); [Young, 2002](#)), these have rarely considered performance relative to targets, or the economic and operational constraints on implementation, and often include considerable mathematical content outside the remit of practitioners. Part of the challenge in preparing the guidelines was therefore to consider both technical and non technical issues in a way which would be accessible to practitioners with a range of expertise in modelling and other skills. In developing the guidelines, a number of similar documents in related fields was also examined, including British Standards documents, Environment Agency guidelines in other disciplines (e.g. contaminated land studies, estuary modelling), hydrological textbooks, and technical manuals, such as a widely used flood design estimation manual for the UK ([NERC, 2000](#)).

2. OVERALL APPROACH

The overall aim in the guideline document was to present in a single location the main technical, economic, operational and other issues to consider in model selection. When selecting a new flood forecasting solution for a catchment or site, a number of factors need to be taken into account, including:

- The physical characteristics of the catchment and river(s)
- The varying levels of data availability and quality
- The cost and time of development
- The technical and economic risks associated with the investment

It is also important to consider whether the resulting forecasts will meet national targets for accuracy and lead time, since often the requirement to meet these targets is a key driver for development. These considerations therefore led to a logical structure for the guidelines as follows:

- Step 1 – Assess technical issues
- Step 2 – Assess economic issues
- Step 3 – Assess associated issues
- Step 4 – Review model selection

For each step, three levels of sophistication were provided where appropriate, depending on the nature of the study to be performed:

- Method A – suitable for a quick scoping study, initial cost estimates etc
- Method B – suitable for a design study
- Method C – suitable for a more detailed assessment for a high cost or high risk design

The overall objective in applying the guidelines is to develop modelling solutions which include specifications for the categories of models required, and additional instrumentation required (or upgrades to existing instrumentation), the likely costs and benefits of the proposed solution, and proposals for any additional studies which are required to further refine the solution. Performance monitoring is also identified as a key component of the approach.

3. KEY STEPS IN APPLYING THE GUIDELINES

3.1. Technical Issues

The technical issues to consider include the physical characteristics of the catchment, the data requirements for model calibration and validation, and the availability of real time data for model operation and real time updating. The general decision was also taken that, rather than designing new systems around existing telemetered instrumentation (as is often the case), the option of installing additional sites should be kept open and considered as part of the economic assessment (and possibly exploratory modelling studies). A four stage approach was devised as illustrated in Figure 3.1.

Similar flowcharts (not shown) were also prepared for the other steps in the model selection process; also, as indicated on the figure, a series of worksheets was prepared to provide structured checklists for performing each step and to assist in documenting the process; for example for quality assurance requirements.

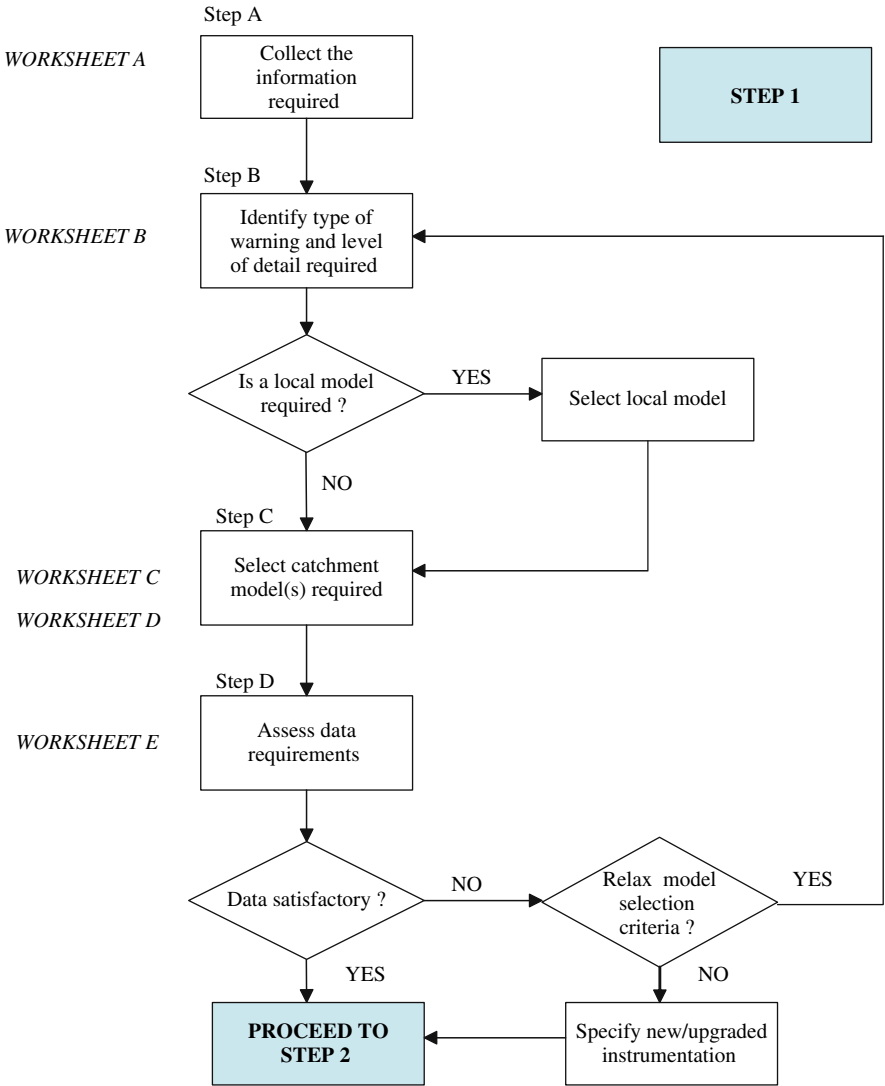


Figure 1. Flowchart for assessment of technical issues

The assessment of physical characteristics considered more than 20 possible factors including catchment descriptors (time to peak etc), artificial influences (reservoirs, control structures etc), and local influences (e.g. backwater, confluence and tidal effects). The concept of “catchment models” and “local models” was also introduced, where a catchment model consists of one or more rainfall-runoff, routing or other categories of models which provide forecasts down to the forecasting point, and a local model consists of a model for forecasting in the immediate

neighbourhood of the forecasting point. For example, a local model might consist of a real time hydrodynamic model relating levels at the forecasting point to levels at low points within a flood defence system within a town (for which an off-line design or scheme model might already be available for conversion to real time). Local models are not always required and are typically justified for high risk locations, or at sites which have hydraulic complications (e.g. control structures, flood gates etc). A simple three point ‘Potential Accuracy Score’ was also introduced to help in assessing the relative accuracy of models, and might be developed further in future versions of the guidelines (e.g. a computerised decision support approach).

One particular issue to consider was how to take account of the wide range of types of model which are potentially available, and a categorisation approach was adopted to guide users through these complexities. [Khatibi and Haywood \(2002\)](#) discuss the inherent concepts and techniques adopted and the resulting categorisation scheme is shown in Table 1. This scheme is in terms of increasing information content in the model output, and acts as a pointer towards selecting modelling solutions with an appropriate level of complexity for the problem under consideration.

Implicit in this scheme is an approach suitable for selecting models based on the reduction of flood risk, particularly when the level of risk at specific at-risk areas

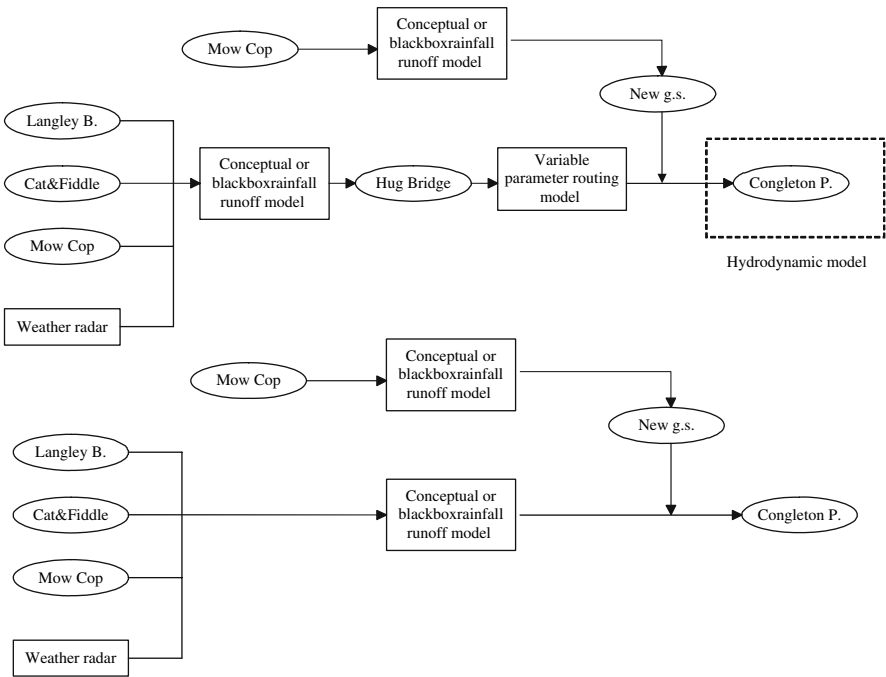


Figure 2. Illustration of alternative modelling solutions for the Congleton example described in Section 4. (g.s = gauging station; ellipse = raingauge)

Table 1. Categorisation Scheme for Types of Model

Category	Variations	Generic steps in information content	Information Content
Rule-of-thumb Models	Triggering actions based on exceeding threshold values at a gauging station or raingauge	Information is built on point observations	Low
Empirical Models e.g. Correlation models	Level-to-level or Flow-to-flow correlation, Time of Travel Maps, Flood Warning Contingency table	Information is abstracted from data points in time and space	
Blackbox (rainfall – runoff) Models	Unit hydrograph; Transfer function (linear, non linear); artificial neural network models	Information is abstracted from full hydrographs at different sites	
Conceptual Models	Lumped or distributed rainfall runoff models, snow melt models	Full hydrographs + storage (tank) features conceptualised	
Discharge Routing or Hydrological Routing	Muskingum models	Full hydrographs + water budgeting for fixed flood waves	
Disturbances propagate in one direction	Kinematic routing Fixed parameter versions	Full hydro-graphs + conservation of mass + a full invariable flood wave	High
Fixed directions of disturbances but variable shapes	Variable parameter diffusion-analogy flood waves	Full hydro-graphs + conservation of mass + a full variable flood wave	
Disturbances propagate in more than one direction	Flood risk mapping or other model converted to real time use	Full hydro-graphs + conservation of mass + conservation of momentum	

can be classified using a three tier approach i.e. low, medium or high. For instance, forecasting at low risk areas would be better served by models of low information content, medium risk areas with medium information content and high risk areas with high information content (this is an assumption but seems a reasonable one).

The categorisation scheme also included a separate entry for real time updating routines, in which forecasts are modified based on observed (telemetred) river levels and flows. The main updating approaches considered were error prediction, state updating and parameter updating, with various types of updating approach within each of these main categories. Of course, various other categorisation schemes could be considered, and hybrid versions of models are often used (particularly in research applications); for example, Transfer Function models may be

combined with an effective rainfall estimation component for real time applications (e.g. [Young, 2002](#)).

The physical nature of flooding problems is similarly diverse and a survey during preparation of the guidelines led to identification of the following priority categories to consider: flashy catchments, confluence problems, constriction problems, attenuating systems (e.g. flood plains), urban catchments, groundwater flooding and complex situations involving structures, braided channels etc.

For the main categories of model and physical system, factsheets were prepared representing successful applications within the UK and overseas, and summary tables were also included in the guidelines summarising the strengths and weaknesses of each approach (data requirements, ease of use, tolerance to data loss, likely accuracy etc).

In the catchment model selection step, national targets for the issuing of flood warnings were incorporated through consideration of typical model accuracies, and the likely lead time to be provided by the model. For example, for the main design approach (Method B), a procedure was developed to assess the forecast lead time required based on catchment response times (e.g. time to peak, river reach lag times), and the estimated times required to:

- Receive telemetry data
- Perform model runs
- Take the decision on whether to issue a flood warning
- Issue the warning

Regarding data issues, the types of data considered included meteorological and river data. For example, potential sources of rainfall data and forecasts which are considered include:

- Tipping bucket raingauges
- Short term Quantitative Precipitation Forecasts (0-6 hours)
- Weather radar estimates of current rainfall ('actuals')
- Radar based (advection) forecasts of rainfall
- Heavy Rainfall Warnings
- Numerical Weather Prediction model outputs

For each data type, checklists were provided to guide users through assessing the types of data required for each type of model, both for calibration and real time operation. The level of detail typically considered requirements for the number of flood events, model initialisation or warm up, catchment averaging of rainfall (for rainfall runoff models), and other factors.

3.2. Economic Issues

Having developed an initial solution, the economic feasibility of that solution can then be assessed. However, when instrumentation, data validation, model calibration and other costs are taken into account, the overall costs of developing a new

forecasting modelling solution can be considerable, and the final decision to proceed is therefore often taken on financial grounds. The two sides to this assessment are the costs and the likely benefits of any new scheme.

Discussions with practitioners revealed that a number of economic assessment techniques were in use, ranging from region-wide assessments to detailed studies for individual sites. The aim in the guidelines was therefore to provide a methodology for use if none was available, or if improvements were required to existing methods.

Following a review of existing techniques, the methodology for calculating the benefits of providing flood forecasting services adopted that initially developed for the appraisal of the benefits of flood warning systems (e.g. National Rivers Authority, [1995]). The basis of the method is to estimate the annual opportunity benefits attributable to improved flood warnings due to the damage which is avoided (e.g. by property owners having time to move carpets, furniture, cars etc) above that which may already be obtained. Public awareness and other social factors are also taken into account leading to the following calculation procedure:

$$\text{Opportunity benefit} = \text{Target benefits} - \text{Existing benefits}$$

where the benefits are expressed in monetary terms (e.g. pounds per year) and are calculated as:

$$\text{Target benefits} = (P_{ft} \times P_i \times P_a \times P_c) \times (PFDA_t - MC_t)$$

$$\text{Existing benefits} = (P_{fe} \times P_i \times P_a \times P_c) \times (PFDA_e - MC_e)$$

P_i = probability that the individual will be available to be warned

P_a = probability that the individual is physically able to respond

P_c = probability that the individual knows how to respond effectively

$PFDA_t$ = target potential flood damages avoided

MC_t = target mitigation costs

P_{ft} = target Reliability (i.e. with proposed improvements)

$PFDA_e$ = existing potential flood damages avoided

MC_e = existing mitigation costs

P_{fe} = existing Reliability

Here, mitigation costs are the costs involved in individuals taking action to reduce flood damages (e.g. taking time off work).

Estimates for the numbers of properties at risk, and damage avoided, can be obtained from historical evidence, analyses using digital terrain models, and detailed hydraulic modelling studies (as available). A spreadsheet included with the guidelines provides typical values for each of these parameters, and for their variations with the standard of flood protection, improved warning lead times, and other factors.

For assessing the benefits from improving flood forecasting models alone (as here), the 'warning dissemination' related factors (P_i , P_a , P_c) are assumed to be unchanged by the new system. The resulting annual value should then be multiplied

by the expected lifetime of the scheme accounting for inflation, depreciation etc in terms of net present values, leading to an overall 'benefit' value over the lifetime of the scheme.

Once the benefits have been estimated, these can be combined with costs to derive a cost benefit ratio. For example, a scheme might be considered to be 'just viable' if benefits exceed costs, and 'justified' if the benefit to cost ratio exceeds 2, although local values and factors might also influence the decision on whether to proceed. Also, for a catchment-wide or regional study, if there are large uncertainties in the costs and/or benefit calculations, then the decision might be taken not to put too much weight on the absolute cost benefit ratios, but rather to look at the relative values to assist with prioritisation of a number of schemes (and in deciding which schemes to proceed with, and which to defer to future years).

In the guidelines, a series of worksheets and unit cost estimates are also provided to assist with cost estimation, and consider:

- Instrumentation and data costs
- Model conceptualisation costs
- Model calibration and maintenance costs
- Model implementation costs
- Other costs (project management, strategic reviews etc)

The estimates provided are initial values which can be replaced by locally derived values where available. It is also the intention that these values will be routinely updated in future updates to the guidelines as the cost knowledge base is developed.

3.3. Associated Issues

Although technical and economic issues are important, in practice a number of other factors can also affect the decision on model selection. Some typical issues to consider at this stage include:

- the main limitations on the modelling solution
- the performance of the model outside its range of calibration i.e. in extreme events
- the ease of model calibration
- the ease of using the model in real time
- the likely accuracy of the chosen solution
- the likely error sources
- automating functionality in any future post event analysis
- the requirements for storing data and forecasts
- ways of monitoring the performance of the operational modelling solutions
- issues in relation to model calibration and recalibration

The guidelines provide a series of checklists for assessing the main factors to consider under each heading, and suggest appropriate conclusions where possible. For example, the following possible methods are described for assessing model uncertainty:

- Assume plausible ranges for the model parameters/input data
- Stochastic sampling of parameters/data
- Combined stochastic and process-based sampling
- Use multiple objective functions
- Derive distributions for the estimates
- Examine the model’s error propagation characteristics

and a simple procedure was tentatively proposed for estimating model accuracy at different lead times. For example, Table 2 shows a worked example for assessing the likely accuracy in forecast levels for a combined rainfall runoff and flow routing model, using error prediction flow updating, assuming a linear transformation of errors in measurement data, linear addition of errors, and a real time updating routine with error propagation characteristics typical of error prediction updating schemes.

This method, whilst only indicative, allows for a range of assumptions regarding error propagation characteristics, updating characteristics, combinations of errors (e.g. linear addition, as here, or addition of variances), and was based on a review of the literature (e.g. Michaud and Sorooshian, 1994; Ogden and Julien, 1994;

Table 2. Example of proposed procedure for deriving first estimates for the variations in model errors with forecast lead time

Element of model providing forecast	Routing component of model		Rainfall Runoff component of model			
	0 hrs	1 hr	2 hr	3 hrs	4 hrs	5 hrs
Assumption						
Assume a 10% error in the measured input flow and rainfall data (%)	10	10	10	10	10	10
Assume a linear transformation of errors for routing and rainfall runoff models (%)	10	10	10	10	10	10
Assume a linear decay in error correction towards zero at the maximum lead time (%)	0	2	4	6	8	10
Assume a rating exponent of 2.0 at the site of interest (%)	0	1	2	3	4	5
Assume a bankful level of 5 metres at the site of interest (metres)	0	0.05	0.10	0.15	0.20	0.25

(Singh, 1997; Sun et al., 2000; Troutman, 1983) and a series of exploratory modelling studies using conceptual and transfer function rainfall runoff models, and a variable parameter flow routing model, which were performed during preparation of the guidelines. However, it is recognised that the issue of error propagation is an active research area at present, and that in future versions of the guidelines this approach could be developed further to take account of the latest research findings (e.g. see Section 5).

3.4. Review Model Selection

The final step in the model selection procedure is to review the resulting modelling solution against a range of qualitative criteria, and if necessary to repeat one or more of the previous steps to refine the solution. For example, it may be that a simpler solution has to be adopted due to budget or other constraints, or a more complex solution explored to obtain the required forecasting performance. The

Table 3. Example of a risk assessment matrix

Factor	Overall weighting	Score for each option		
		Option 1	Option 2	Option 3
Policy and targets				
Likely to meet national high level targets	5	1	1	1
Likely to meet local targets	2	0	1	1
Consistent with existing modelling approaches	5	1	1	0
Compatible with future System Environment	2	0	0	1
Benefit cost ratio satisfactory	5	1	1	0
Costs within budget	5	1	1	0
Risks and assumptions acceptable	5	1	1	1
Operational issues				
Pilot study to introduce new modelling approaches	1	0	1	1
Capable of manual operation	0	1	0	0
Suitable System Environment available	5	1	0	0
Calibration software available	5	1	0	0
Easy to use in real time	2	1	1	1
Staff familiar with the solution	1	1	0	0
Implementation issues				
Can be implemented in the required timescale	5	1	0	0
No further exploratory work required	5	1	1	0
No third party involvement required	2	1	1	0
No site works required	2	0	0	0

guidelines emphasise that good design is often an iterative process, and that often a compromise needs to be reached between cost, benefits, technical feasibility, and other factors.

To help in performing this review, a risk assessment matrix approach was proposed using the following weighting system for each of the factors considered:

- Essential – score 5
- Desirable – score 2
- Marginal benefit – score 1
- Not important – score 0

together with a yes/no (1/0) score for each factor to say whether it meets the criterion in question. An overall score is then calculated by summing the individual weighted scores for each factor. This approach, although subjective, provides a structured way of considering the relative importance of each factor, and aims to focus attention on what is important in the design, and to identify clear ‘winners’ or ‘non starters’ amongst the different options considered. The guidelines also note that the weighting and scoring scheme adopted, and the factors considered, can be adapted for local circumstances.

Table 3 shows an example of this approach for a hypothetical design study which has led to three alternative modelling solutions (Option 1, Option 2, Option 3) of increasing complexity and where the overriding need is for a rapid implementation within a limited budget.

In this example, multiplying out and summing the entries for each option gives the following overall scores:

- Option 1 – 50 points
- Option 2 – 37 points
- Option 3 – 17 points

So, in this case, the most accurate and technically suitable solution (Option 3) obtains a low score due to cost and operational constraints with Option 1 a clear winner (although Options 2 and 3 might be reconsidered in subsequent phases of model development).

4. APPLICATIONS

The first version of the guidelines was presented to the Environment Agency in 2002 at a national workshop for key flood forecasting practitioners, and has been highlighted as good practice in internal documentation. The guidelines also represent perhaps the first structured approach by any national authority to the selection of models for flood forecasting applications. Some notable applications since launch of the guidelines have included:

- Incorporation into the specifications for development of Catchment Flood Warning Management plans for two Environment Agency regions
- Use in deriving indicative cost estimates for models and instrumentation for a ten year regional flood forecasting strategy in a third region

- Inclusion in a generic forecasting model development specification for one Environment Agency region
- Model conceptualisation and initial design studies for several catchments across England and Wales

Initial feedback from users has been largely positive, although has highlighted the need to refine the unit cost estimates as experience is gained in application of the guidelines.

As an illustration of the outputs from this process, the guidelines include several worked examples from which Figure 2 is taken. The figure illustrates two alternative modelling solutions with different accuracies for a new flood forecasting model to be developed for the town of Congleton on the River Dane in North West England; in the uppermost solution, a higher level of modelling accuracy has been specified pointing towards a more complex modelling solution producing a higher information content in the modelled output. In the second, simpler solution, a lesser degree of accuracy is specified, with a correspondingly lower cost of implementation.

Schematics like these can also be presented as itemised lists which, when combined with unit cost estimates for items such as raingauges and individual modelling components, can be used to derive first estimates for overall implementation costs. However, it should be noted that the Dane is a small catchment (145km²), with few complicating features, and the model design and related schematics can be considerably more complex than this example in some situations.

5. DISCUSSION AND CONCLUSIONS

The guidelines have provided for the first time a structured approach to model selection within the Environment Agency, with a number of applications since their initial publication. The introduction of a model categorisation scheme has proved useful as a tool for managing the complexity of model types available, and the inclusion of economic and other factors has assisted in improving upon model selection approaches based purely on technical grounds (e.g. the concept of ‘horses for courses’).

More generally, the exercise of producing the guidelines proved to be an interesting challenge, requiring the development of management tools for presenting a technical subject in a manner which is accessible to users from a wide range of backgrounds, with varying levels of hydrological expertise. Amongst practitioners, the use of flowcharts, checklists, risk assessment matrices, factsheets and worked examples has been positively received, and provides the basis for an auditable approach to model selection.

Perhaps the main question which has arisen has been whether the document should be more prescriptive (a ‘cookbook’) but the authors are firmly of the view that some judgement is required in any solution, and that there may be more than one solution meeting the needs of any given modelling situation. For example,

it is easy to envisage two modelling solutions of differing complexity, both cost beneficial, which meet targets, where the choice of which approach to adopt comes down to the availability of existing software, the skills of the staff who will operate the models, and other operational issues.

The guidelines were also less explicit in associating the information content of model categories with tiered (classified) flood risk levels (e.g. low, medium or high risk) as a guide to model selection. The Agency is presently developing software tools for assessing risk levels based on flood defence condition, probability of flooding and other factors, together with definitions for assessing risk levels at specific classes of risk areas (e.g. Flood Risk Areas, Flood Warning Areas and Flood Watch Areas). These developments together with an assessment of the information content in model categories provide the basis to further develop the guidelines and make the risk dimension explicit. A tentative architecture for incorporating the risk dimension in model selection is discussed by [Khatibi et al. \(2004\)](#).

Another conclusion is that guideline documents of this type should be updated at regular intervals. For example, even in the time since publication, national flood warning targets have been revised, and a decision has been taken to adopt a national flood forecasting system ([Khatibi et al., 2003a](#)) within which models can be incorporated. Guideline documents on estuarine and coastal flood forecasting have also been issued ([Khatibi et al., 2003b](#)), so it is envisaged to produce a single document which combines documents on meteorological, fluvial, estuarine and coastal flood forecasting. Over the longer term, future versions of the guidelines would benefit from analyses of the value added from use of a structured approach, and comparisons of the modelling solutions developed with those developed using more ad-hoc approaches.

The techniques developed could possibly also be applied in other locations, and to other areas in which a structured approach is required to decision making; for example, in the area of flood forecasting and warning, one application might be to the prioritisation of implementation of new flood warning schemes (including warning dissemination systems). If applied outside of a UK context, the guidelines would of course need updating to account for different national targets and procedures, and possibly to include additional forecasting problems (e.g. ice blockages in colder climates, irrigation scheme influences in some locations). The economic approach might also need adapting since the detailed information on damage avoidance may not be available in all situations.

Not surprisingly, the task of preparing the guidelines has also highlighted a number of areas of uncertainty where future research and development is required, whose findings might feed into future releases of the guidelines. Some particular areas which have been identified include automated techniques for post event analysis of model performance, and the relationships between model performance measures for accuracy, reliability and timeliness and national targets for flood warning. On the basis of the present studies, and following a review of previous

exercises into identifying research needs (e.g. [British Hydrological Society, 2001](#); [Casale, 1997](#); [Environment Agency, 2000b](#)) some other projects which were proposed included:

- Development of decision support tools for flood forecasting on fast response catchments
- A review of high level targets for flood forecasting
- Rainfall runoff modelling for ungauged and low benefit locations
- Real time operation and updating of hydrodynamic models
- Evaluation of next generation distributed rainfall runoff forecasting models
- Improved forecasting models for groundwater dominated flooding
- Error propagation and assessment of uncertainty in real time applications
- Evaluation of new blackbox and conceptual approaches to rainfall runoff modelling

A number of these projects have now either been initiated, or have fed into other national research programmes.

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CHAPTER 22

NUMERICAL MODELLING IN COASTAL FLOOD FORECASTING AND WARNING IN ENGLAND AND WALES

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Abstract: This paper reviews the current practice of coastal flood forecasting and warning in England and Wales. The basis of the coastal flood forecasting and warning and recent advances in relevant numerical modelling technology are reviewed and explained. The paper discusses the benefits and opportunities these new technologies can bring and the practical problems, dilemmas and challenges that the service providers and consultants face at present and in the future

Keywords: flood forecast, flood warning, coastal flood and numerical modelling

1. INTRODUCTION

Recent estimates are that 21% of the world's population live within 30 km of the coast and growth in these areas is twice the global trend. In England and Wales, the percentage of the population that live in an area at risk of coastal flooding is even higher. According to the U.K. Government, the east coast counties between the Thames and the Humber Estuaries, are expected to have 322,000 new households between 2001 and 2021; this equates to 10% of England's total projected need. In 1953, this area suffered the country's worst flood in living memory. Accordingly, the pressure to have reliable coastal flood forecasting and warning systems will increase.

Most existing coastal flood forecasting and warning (CFFW) systems in England and Wales were established more than a decade ago. There have been no major improvements in them, possibly because there have been no recent "major" tidal

flood events. The forecasting methods and approaches vary across the country, which leads to inconsistent standards of service. There is a broad consensus amongst the service providers, including the Environment Agency and maritime county councils, that the current CFFW systems are not as reliable as their fluvial counterparts. There is a widespread concern regarding false coastal flood warnings. They are a waste of resources and could cause residents to become complacent and ignore a real flood warning after a number of false alarms.

In contrast with the relatively slow development of CFFW, technologies have continuously improved in both data gathering and numerical modelling in the last decade. There is more and better monitoring data, more reliable meteorological forecasting and IT technology, improved numerical models and faster computers. This paper reviews the current practices in England and Wales and discusses the benefits and opportunities that these new technologies can bring. It identifies the practical problems, dilemmas and challenges that the service providers and consultants are facing at present and in the future.

2. BASIS OF CFFW AND CURRENT PRACTICE IN ENGLAND AND WALES

In this paper coastal flooding refers to that caused by the combined action of waves, wind and water levels. A typical CFFW system in the UK has three main components, namely *forecasting*, *trigger conditions*, also referred to as *critical conditions*, and *inundation mapping*, also referred to as *floodline*. In addition to these, the real-time monitoring and IT infrastructure that handle data transmission, displays, storage/archiving and warning disseminating, are also critical to the performance of a forecasting and warning system but they are beyond the scope of this paper.

2.1. Forecasting

An ideal coastal *forecasting* system should provide forecasts of:-

- water levels, both normal/harmonic tide and surge, at the coast close to shore;
- wave conditions, both wind waves and swell, close to shore;
- wind conditions offshore and inshore;
- overtopping rates of the defence; and
- likelihood of a breach in the defence.

In the UK, the Storm Tide Forecasting Service (STFS) was set up in 1953 after the east coast flooding disaster. STFS, which is operated by the Meteorological Office on behalf of the Department of Environment, Flood and Rural Affairs (Defra), provides 36 hour ahead forecasts of offshore wave and wind conditions and tidal levels at the coast. The Environment Agency is responsible for the provision of forecasts of inshore waves, overtopping rates and breach likelihood.

The STFS offers a primary warning service by providing daily forecasts of tide levels at key locations, known as *reference* stations. However, it does not provide forecasts of tidal levels for all flood risk points on the coast or estuaries. The

distance between reference stations is considered to be too large by most. For example, Immingham is the *reference* station for a large portion of the Humber and Lincolnshire coast (Defra/Environment Agency [2003]). To fill such gaps, the Environment Agency developed a local or *secondary* forecasting service, which uses statistical relationships between reference and forecast stations based on historic data.

At present, the use of wave and wind forecasts in coastal flood forecasting is limited (Defra/Environment Agency [2003]), and the methods which incorporate wave information in forecasting practice vary significantly. For example, some apply offshore wave conditions directly to *trigger conditions* and avoid the process of transforming offshore waves to inshore. The effects of geometry and bathymetry, and the direct use of offshore waves without proper transformation to inshore, may lead to inaccurate estimates of inshore wave conditions. To overcome this, some practitioners use conservative judgment, which may lead to false alarms, whilst others send staff to site to assess the risk of flooding.

Wave transformation matrices, also called *look-up tables*, are used in some areas for inshore wave conditions. Most of these are derived from simplistic one-dimensional or ray tracing wave models. The Environment Agency's North West Region are developing multi-dimensional wave transformation matrices involving wave heights, periods and directions, wind speeds and directions, and surge levels using an a two-dimensional spectral wave model. The system is currently on trial for Morecambe Bay (Defra/Environment Agency [2002]).

Wind forecasts are the least utilized in most regions in England and Wales. At present, the wind effects are usually considered using very crude calculation methods or experience/rules of thumb, and mainly in estuaries where locally generated waves are of importance, such as the Humber. The effect of wind-blown splash and spray is rarely considered but it is regarded by some staff at the Environment Agency as a main cause of coastal floods in certain areas. On a number of occasions, false coastal flood warnings were linked to offshore winds but this is an area where there is almost no research.

The use of wave overtopping calculations in CFFW was introduced very recently in the development of the TRITON system for the North West Region (Defra/Environment Agency [2002]). In other regions, for example North East, the system uses the ratio of freeboard to wave height, which resembles the empirical overtopping formulae for a vertical wall (Besley [1999]). The authors consider that the overtopping rate, which leads directly to estimates of the volume of flood water entering the potentially affected areas, is the most accurate coastal flood indicator. Although significant progress has been made in predicting overtopping, both in empirical formulation based on laboratory data and in numerical models based on solving hydrodynamic equations, application of these recent technologies in the real-time operational environment needs to be further investigated. This is discussed in Section 3.3 of this paper.

In addition to the "attacking" forces of water level, wave and wind, it is also important to recognise the response of coastal defences, including beaches, the so

called “soft” defences, and interaction between these. Changes in beach profile may lead to higher waves at the defence. Heavy overtopping or sustained high sea levels may lead to breach initiation. Understanding of the likelihood of a breach is critical, if reliable forecasts are to be made regarding the flood inundation depths and, hence, risk to life. At present, the likelihood of a breach in the defence is not a major consideration in CFFW in England and Wales (Defra/Environment Agency 2003).

2.2. Trigger Conditions

An alert will be signalled to a duty officer if *trigger conditions* are reached. Based on this and other information, such as telemetric data, a duty officer will decide whether or not to issue a warning. In England and Wales, the Environment Agency operates a four-stage warning system, namely Flood Watch, Flood Warning, Severe Flood Warning and All Clear, that reflects the expected severity and extent of a flood.

Trigger conditions can be water levels, or combinations of water level, wave and wind conditions, or overtopping rates potentially coupled with breach likelihood. Although there are various forms of *trigger conditions* used in England and Wales, a key element is the flood defence condition which includes crest level, defence type and structure/maintenance condition. In addition, the land use and flood water relief systems, such as pumping facilities, need to be considered. In other words, *trigger conditions* are based on a proper assessment, in which flood defence and associated land use and flood water relief systems are evaluated against extreme tidal and metrological conditions. *Trigger conditions* should be updated after a new defence scheme is in place or there is significant alteration of the local wave climate or tidal regime due to coastal and estuarine development.

Trigger conditions were established using very different methods across England and Wales. In Wales, the *trigger conditions* are based on past events; in Southern Region, they were derived using historical information and experience/rules of thumb; In South West Region, they were determined by establishing empirical relationships between cause and effect based on recorded water levels, past flood reports, analysis and site observations (Defra/Environment Agency 2003). Recently, the North West and North East Regions tested the use of wave overtopping models. (Defra/Environment Agency 2003, Black & Veatch 2003).

2.3. Inundation Mapping

Inundation mapping provides a duty officer with information on areas where a warning should be given to the public and emergency services. At present, in Anglian and North West Regions, flood inundation is routinely predicted. Most inundation maps are derived using projection or a simple level balancing model to take account of periodical change of sea levels driven by the tide. Thames Region is

presently considering developing a real-time flood inundation modelling system that involves the use of a one-dimensional or two-dimensional hydrodynamic model.

A typical CFFW system in England and Wales is illustrated in Figure 1. In particular, tidal surges, offshore wave and wind conditions are all provided

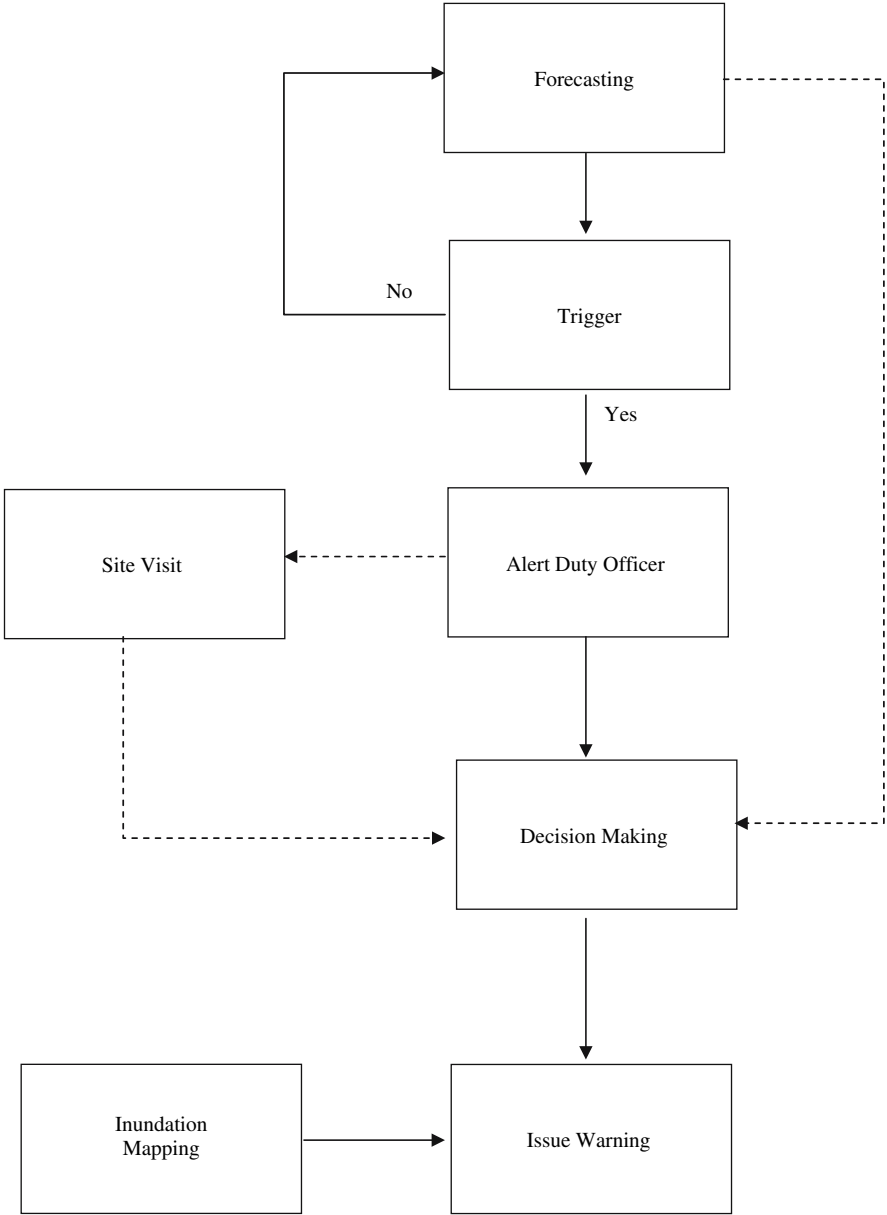


Figure 1. A typical structure of the existing CFFW system in England and Wales

nationally by the STFS. However, the methods of deriving *trigger conditions* and *inundation mapping* vary significantly. The three main components, namely *forecasting*, *trigger conditions* and *inundation mapping*, are equally important to the performance of a CFFW system. However, it appears that the current practice focuses more on *forecasting*. In *forecasting*, offshore wave and wind predictions provided by the Meteorological Office are not fully and properly used in most regions. In reality, the authors found that few coastal floods are caused by high water levels alone; they are often a result of combination of high water levels with high waves. The current practice seems to be designed for events caused by extremely high surges, such as the one in 1953.

3. NUMERICAL MODELLING IN COASTAL FLOOD FORECASTING AND WARNING

The authors believe that the numerical modelling technology can play a key role in modernising the CFFW systems in England and Wales, in particular, improvement in the accuracy and reliability of forecasting and warning for the “middle scale” coastal foods (1 in 5 to 1 in 50 years). This section reviews the recent advances in the relevant numerical modelling technology and the areas where the use of numerical models could make a difference.

3.1. Numerical Modelling in Forecasting Tidal Levels and Offshore Wind and Waves

Numerical modelling has been steadily improved in the forecasting of offshore waves, wind and tidal surges at the coast by the UK Meteorological Office and Proudman Oceanographic Laboratory (POL). Currently, the offshore wave and wind forecasts are provided by Meteorological Office’s European Wave Model, a second generation spectral wave model, with a grid resolution of approximately 35 km. The model divides the wave energy spectrum at each grid point into 13 frequency components (0.04–0.324 Hz) and 16 direction components. Recently, a long-term wave monitoring network, WaveNet (<http://www.cefas.co.uk/wavenet>), funded by Defra, operates in real-time operation. The wave data will be also be used to validate the Meteorological Office’s wave model.

Tidal levels, both astronomical and surge, are provided by the Meteorological Office using POL’s Continental Shelf Model CS3. This has a grid resolution of approximately 12 km except in the Bristol Channel and Severn Estuary, where 4 km and 1.3 km grid resolution are used respectively for astronomical tides.

The authors believe that the current level of the Meteorological Office’s forecasts of offshore wave and wind conditions are adequate for the existing CFFW systems. Further advance of the wave model depends on the mesoscale numerical weather prediction (NWP) models. However, *site specific* tidal propagation models, including both astronomical tides and surges, with a finer grid, would improve the

accuracy of tidal level forecasts in some semi-enclosed waters such as the southern North Sea, Thames Estuary, the Wash and Morecambe Bay.

3.2. Numerical Modelling in Forecasting Inshore Waves

It is considered that the main weaknesses of the current *forecasting* systems are inshore wave conditions and wave overtopping. Offshore waves are transformed into inshore by simplistic methods such as a one-dimensional monochromatic wave model or ray tracing wave model. The exception is the North West Region, where a two-dimensional spectral wave model SWAN (Ris 1997) and a non-linear shallow water equation (NLSW) model AMAZON (Hu et al 2000) were used to establish multi-dimensional transformation matrices. In many cases, inshore waves are overestimated due to ignorance of directional spreading of irregular waves (strictly speaking monochromatic waves do not exist in the ocean), wave breaking, diffraction, etc. However the simplistic modelling approach may also underestimate inshore waves and result in a failure of the CFFW system. For example, the CFFW system failed to provide a warning for Hornsea and Withernsea, Yorkshire, on 1st January 1995. During that event, the damaging waves were from direction 334° which was in offshore direction before passing Flamborough Head, approximately 23 km in north of Hornsea. After waves passed Flamborough Head, the propagation direction was turned by nearly 90° clockwise due to wave diffraction, which was not possible to be modelled by a simplistic one-dimensional model. Nevertheless, a one-dimensional monochromatic wave model or ray tracing model may be useful for ad hoc application in an area with a straight coastline/straight bathymetry contours.

To date, there are two basic types of advanced numerical wave model, namely *phase-resolving* and *phase-averaged* models (Liu and Losada, 2002). Phase-resolving models are based on vertically integrated, time-dependent mass and momentum equations. They require input of a wave train, time series wave data, at the offshore boundary and produce a wave train inshore. Phase-averaged models are based on spectral energy balance equations, which more efficiently transform a group of wave from offshore to inshore. Even though computing power is rapidly increasing and significant progress has been made in phase-resolving models, in particular the highly nonlinear and dispersive wave model, they are still too slow to be used in coastal wave transforming from offshore to inshore. However, the recent research and application (Kobayashi and Wurjanto 1987, Dodd 1998, Hu et al 2000) demonstrates that the phase-resolving model is a useful tool for calculating overtopping. Numerical modelling in wave overtopping is discussed in the following section.

The authors believe the modern two-dimensional spectral wave model is a practical tool for national or regional inshore wave forecasting because it is a well tested technique, which is mathematically compatible with the Meteorological Office's European Wave Model (both are spectral wave models), and the demand on computer power is reasonable. Although a two-dimensional model is more expensive to set up and run compared to a one-dimensional model for ad hoc

application, two-dimensional models will be technically more appropriate and cost effective for regional or national inshore wave forecasting.

3.3. Numerical Modelling in Forecasting Overtopping of Sea Defence

Wave overtopping of sea defences involves wave shoaling, wave breaking, wave run-up, wave reflection and possibly wind effects on water spray. Accordingly, accurate numerical modelling of wave overtopping is a very difficult task. Even in the case of physical modelling, the accurate simulation of wave overtopping is not easy.

There are two basic types of overtopping models, namely *empirical equation* models, based on fitting to laboratory data, and *phase-resolving* wave models, based on solving nonlinear equations. [Besley \(1999\)](#) and [Hedges and Reis \(1998\)](#) provide good summaries of the empirical equation methods and describe the relationships between overtopping discharge and the characteristics of seawalls and waves. However, empirical equation models are based on flume experiments so their application is limited to a small number of sea defences, beach slopes and berm types.

In the last fifteen years, remarkable progress has been made in the simulation of wave overtopping by solving nonlinear equations. [Kobayashi and Wurjanto \(1989\)](#) demonstrated that wave overtopping could be simulated by the use of non-linear shallow water (NLSW) equations. [Hu et al \(2000\)](#) demonstrated that the NLSW equation model could be used for nearly vertical sea walls. However, the NLSW equation approach ignores the detailed structure of breaking wave and replaces it with a steep-front bore. To address this problem, the sophisticated *Volume of Fluid* (VOF) model is a popular solution ([Troch \(1997\)](#)). Recently, [Ingram et al \(2002\)](#) developed a *Surface Capturing* (SC) model based on the two-dimensional incompressible Euler equations, which was reported to be faster than the VOF model.

Despite the remarkable progress in the development of nonlinear numerical models, the authors believe the use of two/three-dimensional nonlinear models is still limited by their computer intensiveness and associated high costs. Recent research and application show that the empirical equation model and one-dimensional NLSW model are practical tools for predicting wave overtopping in CFFW ([Posford Duvivier \(1999\)](#)). The empirical equation model is fast and inexpensive but applicable only to a certain type of man-made sea defence, whilst the NLSW model is suitable for a natural sea defence and man-made sea defence with non-standard profiles. A combination of the empirical equation model and one-dimensional NLSW model can provide a reasonably accurate prediction of wave overtopping rates.

3.4. Numerical Modelling in Forecasting Wind Impact

Most empirical equations for wave overtopping rates were derived from small scale physical model tests, by HR Wallingford and Delft Hydraulics, that were conducted in the absence of wind. Numerical models that are currently available for wave

overtopping also neglect the effects of onshore winds. There is very limited research into the effects of wind on wave overtopping and almost no research on offshore-blown wind. [Ward et al](#) ([1994](#)) summarised the four main causes of onshore wind effects on wave propagation and overtopping:-

- (a) wind-induced set up – higher water levels due to pressure gradients and wind shear at the air/water interface;
- (b) wave spectral changes – local winds may modify incident wave spectra through changes in direction or intensity and affect shoaling as they approach shallow water;
- (c) transfer of potential energy to kinetic energy – onshore winds may cause a transfer of potential energy (wave height) to kinetic energy (surface currents) through wind-induced wave breaking and shear effects; and
- (d) wind advection of splash and spray – waves breaking on a coastal structure could create large quantities of spray and on vertical structures this may produce large vertical sheets of spray. Onshore winds could carry spray over the structure contributing to overtopping.

The wind-induced set up of (a) is included in the Meteorological Office's forecasts of tidal surge at the coast. However, the wind-induced set up inside estuaries and other semi-enclosed waters is not currently considered. Although further investigation is needed to understand the significance of wind-induced set-up, there are no technical difficulties in modelling it for semi-enclosed waters by the use of a fine-grid tidal model, as recommended in Section [3.1](#).

The laboratory work on effects of (b) and (c) is not conclusive because mechanically reproduced a wind/wave spectrum does not necessarily reproduce the shape of the individual real waves ([Ward et al](#) [1994](#)).

With regard to the wind effect (d), [Waal et al](#) ([1996](#)) suggest that the upper limit for the effect of wind on spray for a vertical wall is approximately a factor of 3. [Ward et al](#) ([1994](#)) found that a wind speed of 6.5 m/s (Beaufort Force 4) had little effect on overtopping but a wind speed of 12 m/s (Beaufort Force 6) or higher, greatly increased both run up and overtopping. It is clear that much more research is required before the wind effects can be accurately predicted. At present, the wind blown splash and spray may be considered by multiplying (or dividing) overtopping rates by a factor of 1 to 3 at vertical walls when onshore (or offshore) wind speed exceeds 5-6 Beaufort scale.

3.5. Numerical Modelling in Forecasting Breach Likelihood

It must be recognised that predicting the onset of structural failure, or breach initiation, is notoriously difficult. Predicting breach formation (breach growth, maximum size and invert level) is equally problematic and at present beyond the capabilities of most numerical tools. Although considerable work has been carried out in the past and continues today, such as breach growth in sand dikes

(Visser 2001) and the EU funded project IMPACT (www.impact-project.net) which includes research into numerical modelling of breaching formation, mathematical understanding in breach initiation and formation is still very limited (Morris and Hassan 2003). Nevertheless, despite the poor performance of breach models, breaching of sea defences is of considerable importance both in determining flood risk and to the effectiveness of CFFW services. For the next five years, we may have to rely on rule of thumb or other simplistic methods for predicting breach likelihood.

3.6. Numerical Modelling of Inundation

In contrast to the above fields, numerical modelling technology is reasonably well developed for predicting flood inundation. The non-linear shallow water (NLSW) equations are mathematically adequate to describe flood wave propagation in both natural flood path and urban areas. Even moving hydraulic jumps and supercritical flow can be properly simulated if the NLSW equations are fully and correctly solved (Hu et al 1998). The main problems in flood inundation modelling are a need for good quality topographic and field data for model calibration (in particular, the friction term for vegetation and small-scale man-made structures like houses and fences) and the associated cost in data collection and processing. In urban areas, the cost is even higher because a high resolution two-dimensional model may be needed to take account of buildings and streets.

4. DISCUSSIONS ON THE FUTURE IMPROVEMENT AND PRACTICAL PROBLEMS

The above reviews indicate where improvements can be made to the existing CFFW systems in England and Wales. However, with respect to implementation, there are a few practical problems. This section highlights the key practical problems and dilemmas, and discusses the authors' vision of the future CFFW system.

Firstly, *forecasting*, *trigger conditions* and *inundation mapping*, are equally important to the performance of a CFFW system. This means that improving the *forecasting* part may not necessarily improve overall performance. In particular, the *trigger conditions* should be compatible with the *forecasts*. However, it is usually a lot more costly to modernize *trigger conditions* than a *forecasting* system, and *trigger conditions* are often disregarded after a new defence is constructed.

Secondly, we need to consider running numerical models for inshore waves and overtopping either online or offline; this is an issue that arises frequently in discussions of forecasting and warning modelling systems. It may be impractical to use some of the more complex models in a real-time forecasting environment, due to the length of time required to run the models and the potential numerical

instabilities. The offline method is a practical solution to this problem but there are two main drawbacks. Firstly, the use of a “translation” matrix, from pre-run of offline models, may result in a loss of accuracy, since the resolution of the “translation” matrix is limited. Secondly, the matrix may need to be updated after new bathymetric data or a new version of numerical model becomes available. For example, the offshore-to-inshore wave transformation model used limited inshore wave data in the calibration exercise when the original TRITON system was set up for the Agency’s North West Region. With more inshore data from wave buoys becoming available in the near future, the model parameters will be subject to re-adjustment.

However, the updating process is much simpler in the offline approach than the online one in which the modelling system needs to be thoroughly tested with new bathymetric data or new version of models. It may be too optimistic to predict that the necessity for offline modelling may gradually disappear over the next few years as computer speed continues to increase. Numerical models are continuously being improved, which may require more computing efforts to facilitate, and the demand for model accuracy is increasing. Consequently, advances in computer speed may never satisfy the needs of the online system.

In CFFW, the Meteorological Office have been operating the online meteorological and offshore wave model for many years. This might lead to a conclusion that we should use the online option for the transformation from offshore to inshore. However, the authors argue that it may be more economic to use the offline option for the wave transformation because of the potentially high cost in IT infrastructure for online real-time forecasting. The boundary conditions of the inshore wave model are much simpler than the Meteorological Office offshore wave model, which means that it is possible to produce a high-resolution wave transformation matrix to satisfy the accuracy requirement at a reasonable cost.

It is a popular debate whether the inshore wave modelling system should be regional or national. The national approach is more cost effective both in the initial set-up and routine operation, and it may be economically viable to operate a national inshore wave modelling system using supercomputers. The main drawback of the national approach is its potential inflexibility in model revision and updating. The grid resolution of the inshore wave model needs to be refined as a result of local or regional development and event reviews.

For wave overtopping and flood inundation, the online model approach appears to be more attractive because of high nonlinearity of relationships between inshore wave and surge conditions, overtopping rates, and inundation depth and extents. However, computer speed is not yet fast enough for the use of the NLSW equations model in real-time online operation.

The final dilemma arises from ever improved data collection and monitoring technology introduced in the last decade, in particular, LIDAR (Light Detection and Ranging), an airborne mapping technique, and WaveNet, a real-time wave monitoring system. Can we continue to blame poor data and monitoring in the future?

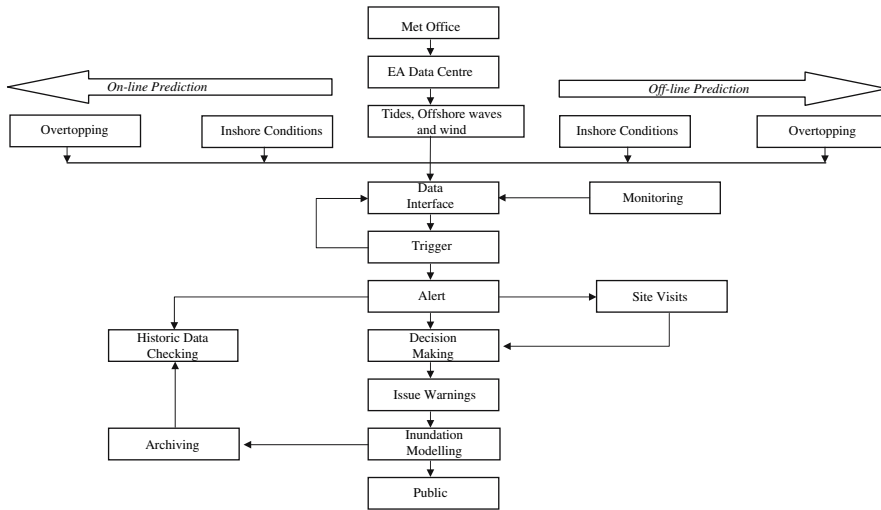


Figure 2. Illustration of the Future CFFW system

5. CONCLUSIONS

Numerical modelling, data collection and monitoring and IT technologies have been significantly improved during the past decade, but most existing CFFW systems in England and Wales have not benefitted from these advances. The existing CFFW systems appear to be designed for events caused by extremely high surges and not the more frequent floods caused by a combination of tidal surges, waves and wind. The authors believe that the numerical technology can play a key role in modernizing the CFFW system in England and Wales, particularly improving the ability of forecasting “middle scale” coastal floods. The main weaknesses of the current forecasting system are considered to be inshore wave and overtopping predictions. In addition to the use of numerical modelling technology, the authors also point out the importance of modernising and updating trigger conditions, and balanced investment in all three key components, namely *forecasting*, *trigger conditions* and *inundation modelling*. Figure 2 illustrates a structure of the future coastal forecasting and warning system that, the authors believe, is achievable in the near future.

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SECTION V

FLOOD RISK MANAGEMENT POLICY

CHAPTER 23

REFLECTIONS ON THE CHALLENGES OF EU POLICY-MAKING WITH VIEW TO FLOOD RISK MANAGEMENT

Actors, processes and the acquis communautaire

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Abstract: Europe has a long history of devastation caused by floods. Each flood event triggers dynamic spatial and temporal mechanisms, which include the mobilisation of many multi-disciplinary actors, setting up and/or revision of many administrative and operational processes, and entry into force and/or update of legal frameworks. Depending on geographical extent of the flooding coupled with national *modus operandi* of countries, the above-mentioned mechanisms may take place at local, regional and national levels. However, as floods can also be a transboundary phenomenon, and as events in one country are no longer isolated but are strictly related to progress towards increased social cohesion and competitiveness within the European Union (EU), European initiatives dealing with floods and other major hazards have gained momentum and are considered a strategic objective in the EU. This is evidenced by the establishment of the EU Solidarity Fund¹ that was set up in the aftermath of the Central European flooding in August 2002 “providing financial assistance to contribute to a rapid return to normal living conditions in the disaster-stricken regions”. The decision-making process prescribed in the Treaty establishing the European Community² (TEC) would govern the legal basis for any

¹ COUNCIL REGULATION (EC) No 2012/2002 of 11 November 2002 establishing the European Union Solidarity Fund.

² The Treaty establishing the European Community is one of the founding treaties of the EU. It incorporates the rules and procedures for decision-making amongst the institutions of the EU and it explains every area in which the European Union can legislate.

potential flood risk management initiative at EU level and would mainly be based on Article 174, comma 2 of the TEC

This paper introduces the reader to the EU decision-making mechanism by briefly describing the actors of the EU inter-institutional decision-making process with view to flood risk management. It also gives an overview of the existing European Commission (CEC) efforts in the field and portrays the challenges the EU has to face given the state-of-the-art of flood risk management at EU level. Finally, a glimpse of a strategy to provide added-value through EU policy endeavours to complement national initiatives are proposed

Keywords: *acquis communautaire*, European Commission, EU, risk management, policy, prevention, mitigation

1. FLOODS IN EUROPE

Disasters, such as floods, tend to refresh the memories of people and governments on how important risk management is when dealing with such events, with view to reducing their impacts on society. A series of inundations events have hit Europe (Easter 1998 and Autumn 2000 floods, UK; Summer 2002 floods of Central and Eastern Europe [Austria, Czech Republic, Germany, Hungary, Italy, Slovakia, Spain and the UK], Autumn floods of 2003 [Italy and France]), which have raised the level of awareness, and in some cases they have triggered significant institutional initiatives in various government levels, including EU level. This paper aims to bring EU policy and initiatives related to flood risk management closer to the scientific community and the public. It portrays the EU inter-institutional decision-making process and briefly describes European Commission efforts. Finally, gaps are identified and proposed ways forward are provided, with the goal of providing EU added-value to complement national initiatives.

1.1. Flood Risk Management in some European Countries

Countries in Europe have, to some degree, experienced flood disaster imprinting in their history (Vetere Arellano et al., 2003) and have learnt many lessons from such events (Environment Agency, 2001; European Environment Agency, 2001; Colombo and Vetere Arellano, 2002). Thus, flood risk management in each country will be dictated by their flood imprinting, i.e. history of past events that affected a given society, history of how past events were dealt with, history of

³ "Community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source..."

⁴ CEC: Commission of the European Community, also known as the European Commission.

how lessons learnt were incorporated into the coping capacity of a society. This has triggered the preparation of guidance documents (UN-ECE, 2000; Colombo et al., 2002; European Commission, 2002; European Commission, 2004) and legislation (European Union, 2002), usually in the aftermath of significant floods, which have been carried out at various levels of government (international, national, regional and local). Table II offers a glimpse of leading competent authorities and national legal acts addressing flood-related issues in some European countries. It can be observed that: i) there are many institutions involved in flood risk issues, ii) there are many legal acts that address floods, iii) all almost countries have flood risk management plans.⁵

In addition, management efforts have also been made at a basin-wide scale, particularly by the various water body consortia, such as the International Commission for the Protection of the Rhine River,⁶ International Commission for the Protection of the Danube River⁷ and the International Commission for the Protection of the Black Sea.⁸ Flooding is a transboundary issue, thus burden-sharing of problems and benefit-sharing of exchange good practice is essential in the common quest to improve and promote a sustainable flood risk management strategy in Europe.

2. THE ACQUIS COMMUNAUTAIRE WITH VIEW TO FLOODING

To complement these national flood risk management activities, the EU contributes its share though the *acquis communautaire*, which set of common rights and obligations that bind all the Member States (MS) together within the EU.

It is composed of three interdependent types of legislation: primary, secondary and case law.

Primary legislation: consists of the Treaties and other agreements having similar status, which is agreed by direct negotiation between Member State governments and are subject to ratification by the national parliaments. The EU is based on three treaties⁹ *Treaty establishing the European Economic Community*¹⁰ (TEC), *Treaty establishing the European Atomic Energy Community*¹¹ (Euratom) and the *Treaty on European Union*¹² (TEU).

⁵ It is not within the scope of this paper to analyse in depth national legislation.

⁶ <http://www.iksr.org>

⁷ <http://www.icpdr.org/flash.htm>

⁸ <http://www.blacksea-commission.org/Main.htm>

⁹ Until 23 July 2002, there were four founding treaties. After 50 years of existence, the Treaty establishing the European Coal and Steel Community expired. (http://europa.eu.int/ecsc/index_en.htm)

¹⁰ It is now the *Treaty establishing the European Community* (TEC). It was signed in Rome on 25 March 1957, and entered into force on 1 January 1958. (http://europa.eu.int/abc/treaties_en.htm; http://europa.eu.int/eur-lex/pri/en/oj/dat/2002/c_325/c_32520021224en00010184.pdf)

¹¹ This treaty is also known as the Euratom Treaty, and was signed and entered into force at the same time as TEC.

¹² This is also known as the Maastricht Treaty, as it was signed in Maastricht on 7 February 1992 and entered into force on 1 November 1993. (http://europa.eu.int/abc/treaties_en.htm; http://europa.eu.int/eur-lex/pri/en/oj/dat/2002/c_325/c_32520021224en00010184.pdf)

Table 1. Leading competent authorities and national legal acts addressing flood issues in some European countries*

Sector/ Country	Lead competent authority (ies)	Main national legal acts flood-related issues	Flood risk management plan
Austria	– Federal Ministry for Agriculture, Forestry, Environment and Water Management (BMLFUW) – Federal Ministry for Transport Innovation and Technology (BMVIT) – Waterways Management Office (WSD)	– Water Act – Hydrology Act – Torrent Control Act – Water construction financing Act, (WBFG) – Disaster Relief Fund, (KATFG) – Ordinance on risk mapping, (VO GZPL) – Guidelines of risk mapping (RL GZPL – RIWA-T) – Guidelines on hazard mapping torrent and avalanche control – Technical guidelines for torrent and avalanche control (TR-WLV) – Technical guidelines for water management – Guidelines for cost-benefit analysis on torrent/avalanche control measures	Yes
Bulgaria	– Civil Protection Agency – National Institute of Meteorology and Hydrology	– Constitution of the Republic of Bulgaria, Art. 16 concerning the obligation of citizens to help the Government and the municipality in case of natural or man-made disaster. – Bulgarian legislation regulating the civil protection activities is based on the Council of State's Directive 265 of 1978, as well as the Rules on the Implementation of the Civil Defence Directive, promulgated in 1988 (amendments and addenda: 1990; 1999; 2001). – Council of Ministers Enactment No 18 of 1998, Rules on organisation, prevention and mitigation of consequences of natural and technological disasters.	–

Czech Republic	– Ministry of the Environment – Ministry of the Interior – Central Flood Protection Commission	– Water Act No. 254/2001 Coll. – Law No. 239/2000 Coll., on the Integrated Rescue System – Law No. 240/2000 Coll., on Crisis Management	Yes
Estonia	– Ministry of Internal Affairs, Estonian Rescue Board – Ministry of the Environment – Estonian Meteorological Institute	– Environmental Supervision Act – Environmental Monitoring Act – Emergency Preparedness Act	–
France	– Ministry of the Environment – Ministry of the Equipment, Housing and Transport – Ministry of the Interior	– Law of 1995 for the reinforcement of the environment protection, in particular the Prevention of Natural Hazards Plan (PPR) – 24/01/1994 Circular on flood prevention and flood prone management – 02/02/1994 Circular on urban development control in flood prone areas – 24/04/1996 Circular on building and existing engineering works arrangements in flood prone areas	Yes
Hungary	– Water Directorates (I, II, III scale) – National General Water Directorate – National Directorate General for Disaster Management (NDGDM) – National Technical Managing Headquarters [base: Ministry of Environment and Water Management]	– Act LXXIV of 1999 on the management and organisation for the prevention of disasters and the prevention of major accidents involving dangerous substances (Act on Disaster Management) – Act LVII of 1995 on water economy – Government Decree No. 232/1996 (XII.26.) on the rules of the defence against harm to waters – Decree No. 10/1997 (VII.17.) KHVM on defence of flood and inland water – Government Decree No. 179/1999 (10 December)	Yes

(Continued)

Table 1. (Continued)

Sector/ Country	Lead competent authority (ies)	Main national legal acts flood-related issues	Flood risk management plan
Italy	– Ministry of Environment – Ministry of Interior	– The law 183/89 on soil protection prompting a river basin management plan – Law 225/92 on Civil Protection – Law 493/93 provides possibility to fragment the basin plans in individual sectors (Piani stralcio); the Plan for Hydrogeological Asset (PAI) is one example – Legislation Decree 180/98 (Sarno Decree) where basin authorities must prepare a Plan for Hydrogeological Asset (PAI) within 30 June 1999, along with an Extraordinary Plan where only very high risk areas for people, infrastructure and environment should be identified – Law 267/98 on creating emergency plans for flood risk areas geared to protect the citizens – Legislation Decree 297/2000 (Soverato Decree), which was converted into the Law 365/2000 on creating emergency plans for flood risk areas, including prevention measures, pre-alert and warning systems	Yes
Latvia	– Ministry of Interior – Ministry of Regional Development and Municipal Affairs – Ministry of Environment – Latvian State Fire and Rescue Service (SFRS) – Latvian Hydrometeorology Agency (LHA)	– Civil Protection law (15.12.1992) – Spatial Planning Law (2002.05.22) – Law “On safety of hydroelectric plants hydro technical buildings” (07.12.2000) – Cabinet of Ministers regulations No 247 (1998.07.05) “State Emergency Operative Commission Regulations”	Yes

	- State Holding Company "Latvenergo	- "National Civil Protection Plan" accepted by the order of Cabinet of Ministers Nr.452 of July 16, 2003. - Cabinet of Ministers regulations Nr. 423 (2000. 12. 05) "Regulations on Spatial plans" - Cabinet of Ministers regulations Nr.515 (2002.11.26.) "National planning regulations" - Cabinet of Ministers regulations No 257 (2001.06.19) "Regulations on safety programmes and declarations of hydroelectric plants hydro technical buildings" - Cabinet of Ministers regulations Nr. 94(2003.02.25) "Methodology of setting up of Protective areas in water aquatorium above and below dams" - Cabinet of Ministers regulations Nr.283 (2003.05.27) "Regulations on plans and action programs for management of river basins". - Draft of Cabinet of Ministers regulations "National significance high-risk territories"	Yes
Lithuania	- Civil Protection Department at the Ministry of Defence: Emergency management and coordination - Ministry of Environment: Monitoring and laboratory control - Fire Protection and Rescue Department at the Ministry of Interior: Rescue operations	- Governmental Decree No. 554 p on Criteria of Natural and Catastrophically Hydro meteorological Phenomenon in the Territory of Lithuania Republic and in the Economic Zone of Baltic Sea, adopted on 02 June 1992 - Governmental Decree No.727p on Informing of Population by National Radio and Television in the case of Accidents, Catastrophes, Natural Calamities, adopted on 17 July, 1992 - Governmental Decree No. 766p on List of Civil Protection Signals, adopted on 30 July 1992	

(Continued)

Table 1. (Continued)

Sector/ Country	Lead competent authority (ies)	Main national legal acts flood-related issues	Flood risk management plan
		– Governmental Resolution No. 757 on Utilisation (employment) of Civil Aviation due to Liquidation Consequences of Natural Calamities and Emergency Situations adopted on 09 October, 1992 – The Civil Protection Law No. VIII-971 adopted 15 December 1998 – The Order of Commander Lithuanian Armed Forces No. 241 on Interaction activities among Lithuanian Armed Forces and County Administrations in the case of Emergency Situations, adopted on 20 September, 1999 – The Governmental Resolution No. 112 on Confirming of Regulation for Evacuation of Population, adopted on 01 February 2000 – The State Plan of Rescuing Works and Liquidation of Flood Consequences in Klaipėda County, adopted on 07 February 2000 – Governmental Resolution No. 216 on Criteria of Emergencies, adopted on 24 February 2000 – Governmental Resolution No. 440 on The Procedure of stockpile, storage, renewal, usage and delivering of the national reserves of civil protection means to utilisation place, adopted 17 April 2000 – Governmental Resolution No. 417 on Confirmation of Regulations for Execution of Search and Rescue works by Aviation, adopted 13 April 2001	

Netherlands, The	- Ministry of Transport, Public Works and Water Management - Ministry of Spatial Planning, Housing and the Environment - Ministry of Agriculture, Nature Protection and Fisheries - Ministry of Home Affairs	- Governmental Resolution No. 1485 on Confirmation of Programme for Flood Preparedness and Liquidation Flood Consequences in Klaipeda and Taurage Counties, adopted 19 September 2002 - Order of Minister National Defence No. 1785 on Confirmation of Calendar Plan of Civil Protection and Rescue System Activities in the Case of Flood Danger threatening in the Downstream Region of Nemunas River and when it occurred, adopted 17 December 2002 - Order of Minister National Defence No. V-586 on Confirmation of Regulations of Information for Emergency Management Centre in the case of Emergency Situation, adopted 02 June 2003	Yes
	- Ministry of Transport, Public Works and Water Management - Ministry of Spatial Planning, Housing and the Environment - Ministry of Agriculture, Nature Protection and Fisheries - Ministry of Home Affairs	- Disaster Act 1985 - Water Administration Act 1900 - Rivers Act of 1908 - Delta Act - Delta Damage Compensation Act - Act on Pollution of Surface Waters - Groundwater Act - Water Management Act - Delta Act Large Rivers - Water Embankment Act - Act of State Water Authority Operations - Water Board Act	

(Continued)

Table 1. (Continued)

Sector/ Country	Lead competent authority (ies)	Main national legal acts flood-related issues	Flood risk management plan
Norway	– Ministry of Petroleum & Energy – Norwegian Water Resources and Energy Directorate – Ministry of Justice and the Police – Directorate for Civil Protection and Emergency Planning – Ministry of the Environment – Norwegian Pollution Control Authority – Ministry of Health – Norwegian Institute of Public Health – Ministry of Agriculture – Norwegian Agricultural Authority	– Water Resources Act – Civilian Defence Act – Planning and Building Act with guidelines for land use in areas with a risk of flooding – Pollution Control Act – Natural Damage Assistance Act	Yes
Poland	– Institute of Meteorology and Water Economy – National Board of Water Management (deadline of implementation: 01.01.2004) – Leaders of local and governmental authorities at each administrative level (commune, district, province, state) – National Rescue and Fire-fighting System (the State Fire Service, Voluntary Fire Brigades)	– Water Act – State of Disaster Act (during implementation) – Fire Protection Act – State Fire Service Act	Yes
Romania	– Ministry of Waters and Environmental Protection	– Governmental Decision no. 209/1997	Yes

Slovak Republic		– Governmental Decision no. 210/1997 – Governmental Decision no. 638/1999		
		– Ministry of Environment of Slovak Republic, Water Protection Department – Ministry of Interior of Slovak Republic, Office of Civil Defence – Slovak Environmental Inspection – Slovak Hydro Meteorological Institute	– Act on Slovak Hydro Meteorological Institute – Year 1953 – Act No. 42/1994 on civil safety – Act No. 129/2002 on integrated rescue system – Act No. 387/2002 on national emergency management	Yes
		– Ministry of the Environment, Spatial Planning and Energy – Ministry of Defence, Administration for Civil Protection and Disaster Relief	– Land – Use Management Act (not yet published in the OJ RS, adopted by the Parliament on 29th Nov 2002) – Act on the Protection Against Natural and Other Disasters (OJ RS 64/94, 33/2000, 87/2001). – Water Act (OJ RS 67/2002) – Act on ensuring means to cover intervention measures to limit the consequences of floods that affected Republic of Slovenia from September to November 1998 (OJ RS 86/98)	Yes
Spain	– Ministry of Interior – Directorate General for Nature Conservation – Ministry of the Environment	– Law 2/1985 of 21 January on Civil Protection defining the functions and general organisation of Civil Protection – Royal Decree No. 692 of 27 March 1981 concerning coordination of the assistance destined to repair the damage or relieve the areas affected by an emergency or natural disaster – Royal Decree No. 1378 of 1 August 1985 concerning the resources to be provided for controlling cases of serious risk, disaster or public calamity		

(Continued)

Table 1. (Continued)

Sector/ Country	Lead competent authority (ies)	Main national legal acts flood-related issues	Flood risk management plan
Switzerland	– Federal Office for Water and Geology	– Royal Decree of 26 October 1990 establishing the Special Committee of the International Decade for Reducing Natural Disasters – Federal Law on Flood Control (Wasserbaugesetz WBG, 1991) – Ordinance on Flood Control (Wasserbauverordnung WBV, 1994) – Federal Law on Land-Use Planning (Raumplanungsgesetz RPG, 1979) – Guidelines: “Flood Control at Rivers and Streams” 2001 – Guidelines: “Addressing Flood Hazards in Effective Land use Activities” (Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten, 1997)	Yes
	– Swiss National Meteorological Service (weather monitoring and forecasting)		
	– Swiss Federal Institutes of Technology at Zurich and Lausanne		
	– Swiss Federal Institute for Forest, Snow and Landscape Research at Birmensdorf		
United Kingdom, only England	– Environment Agency (EA)	– PPG25 Planning Policy, Guidance, Development and flood Risk (DTLR, 2001)) – MAFF High Level Targets for Flood Defence and the Elaboration of the Environment Agency’s Flood Defence Supervisory Duty – Preparing for floods (DTLR, 2002) – EA and MAFF Catchment Flood Management Plans	Yes
	– Department of Environment, Food and Rural Affairs (DEFRA) - former Ministry of Agriculture, fisheries and food (MAFF)		
	– Department of Transport, Local Government and the Regions (DTLR)		
	– Office of the Deputy Prime Minister (ODPM)		

- EA Response to the Independent Report of the Easter 1998 Floods Action Plan
- Lessons Learned Autumn 2000 Floods (EA, 2000)
- Flood Risk Area Mapping
- 20001 EA publicity material for the Flood Awareness Campaign
- Flood Warning Plans
- Inland and Coastal Flood Emergency Plans
- Strategy for flood and coastal defence in England and Wales (MAFF, 1993)
- National Appraisal Assets at risk from flooding (MAFF, 2000)
- Flood and coastal defence appraisal guidance: approaches to risk (MAFF, 2000)
- Shoreline Management Plans: a guide for coastal defence authorities (DEFRA, 2001)
- Strategy for flood risk management (EA, 2003)

N.B. For Wales, the Technical Advice Note 15 (TAN15) prepared by the Welsh Assembly on development and flood risk will soon be published.

*Information from Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Poland, Romania, Slovak Republic and Slovenia taken from **Wood et al., 2003**.

Although flooding, along with other natural hazards, is not directly mentioned in any of these Treaties, they are indirectly addressed in:

Article 2 of the TEC:

"The Community shall have as its task...to promote throughout the Community...a high level of protection and improvement of the quality of the environment, the raising of the standard of living and quality of life, and economic and social cohesion and solidarity among Member States."

This article indirectly specifies what the overarching objective of EU action should be. With this in mind, flooding is one of the many threats on the territory that should be addressed.

Article 3 of the TEC:

"For the purposes set out in Article 2, the activities of the Community shall include...the strengthening of economic and social cohesion;...a policy in the sphere of the environment;...the promotion of research and technological development;...a policy in the sphere of development cooperation;...measures in the spheres of energy, civil protection and tourism."

Article 3 describes which policy areas the EU can act in. The above quote highlights those areas directly affecting flood issues.

Article 6 of the TEC:

"Environmental protection requirements must be integrated into the definition and implementation of the Community policies and activities referred to in Article 3, in particular with a view to promoting sustainable development."

Article 6 specifies the importance of integrating environmental issues in all the policy sectors of the EU. This is part of the Sustainable Development Strategy launched at the Gothenburg European Council in June 2001 (European Commission, 2001). For floods, this implies that sustainable development strategies should be promoted and, ideally and as soon as possible, incorporated into flood risk management on the EU territory. This is not an easy task, as flood risk management touches various sectors that would need to work together in a coordinated manner. Furthermore, pace of progress, prioritisation of resources, direction of action and degree of inter-sectoral communication in one sector does not necessarily occur in symbiosis with one another.

Article 174, comma 2 of the TEC:

"Community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source..."

The above article basically indirectly implies that flood risk management in the EU should be carried out in line with the precautionary principle (European Commission, 2000) and should focus on prevention.

Secondary legislation: is defined by different articles in the Treaties that describe the forms of the *acquis*: *regulations*¹³ *directives*¹⁴ *decisions*¹⁵ *recommendations*¹⁶ and *opinions*¹⁷. There are various types of secondary legislation that have addressed flooding to some degree. This is summarised in Table 2, which is not meant to be an exhaustive list but an overview of flood-related second legislation. At present there are no case laws that address flood-related issues.

At EU level, decision making implies the interaction between the **institutional triangle**: *Council of the European Union*¹⁸ *European Parliament*¹⁹ and *European Commission*,²⁰ along with the *Economic and Social Committee*²¹ and the *Committee of the Regions*²². The rules for this legislative procedure are laid down in the Treaties, which dictate in which areas the EU can act (Borchardt, 2000).

The co-decision procedure²³ which is described in Article 251 of the TEC, is the main legislative process that would be used, if a legislative initiative on floods were to be initiated by the European Commission.

3. THE MAIN POLICY AREAS ADDRESSING FLOOD-RELATED ISSUES WITHIN THE EUROPEAN COMMISSION²⁴

The European Commission has the right of initiative with view to policy-making within the EU. It has various Directorates General that address flood-related issues and has many activities that have contributed to improving flood risk management

¹³ Described in Article 249 (TEC): "A regulation shall have general application. It shall be binding in its entirety and directly applicable in all Member States."

¹⁴ Described in Article 249 (TEC): "A directive shall be binding, as to the result to be achieved, upon each Member State to which it is addressed, but shall leave to the national authorities the choice of form and methods."

¹⁵ Described in Article 249 (TEC): "A decision shall be binding in its entirety upon those to whom it is addressed."

¹⁶ Described in Article 249 (TEC): "Recommendations... shall have no binding force."

¹⁷ Described in Article 249 (TEC): "...opinions shall have no binding force."

¹⁸ http://europa.eu.int/institutions/council/index_en.htm

¹⁹ http://europa.eu.int/institutions/parliament/index_en.htm

²⁰ http://europa.eu.int/institutions/comm/index_en.htm

²¹ <http://www.esc.eu.int>

²² <http://www.cor.eu.int>

²³ "The codecision procedure... gives the European Parliament the power to adopt instruments jointly with the Council. The procedure comprises one, two or three readings. It has the effect of increasing contacts between the Parliament and the Council, the co-legislators, and with the European Commission. In practice, it has strengthened the Parliament's legislative powers in powers in the following fields: ...environment (general action programme)... and research (framework programme)".

(<http://europa.eu.int/scadplus/leg/en/cig/g4000c.htm#c4>)

²⁴ Since this paper was submitted in autumn 2004, the European Commission has written a Proposal for a Directive on the assessment and management of floods on 18 January 2006. This has triggered the EU co-decision procedure between the European Parliament and Council, along with an opinion from the European Economic and Social Committee. Information and key documents can be accessed at: http://ec.europa.eu/environment/water/flood_risk/key_docs.htm

Table 2. Secondary legislation that deal with flood-related issues, brief description of flooding aspect addressed, and the flood risk management phase

Type of secondary legislation	Name of secondary legislation that deals with flood-related issues to some degree	Brief description of flood-related aspect addressed	Flood risk management phase
Regulation	Ex 1) COUNCIL REGULATION (EC) No 2012/2002 of 11 November 2002 establishing the European Union Solidarity Fund	It was established in the immediate aftermath of the Summer 2002 floods in Central Europe. It has been created to rapidly mobilise funds in response to emergency situations (e.g. floods), in order to assist disaster-stricken areas to return to similar conditions before the event occurred. It states that there are other instruments in the EU that already provide financial support for the risk prevention phase (economic and social cohesion instruments).	recovery
	Ex 2) REGULATION (EC) No 2494/2000 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 7 November 2000 on measures to promote the conservation and sustainable management of tropical forests and other forests in developing countries	It states that financial resources should be set aside to protect forests where deforestation has led, or threatens to lead to flooding.	recovery and prevention
	Ex 3) COUNCIL REGULATION (EC) No 1257/1999 of 17 May 1999 on support for rural development from the European Agricultural Guidance and Guarantee Fund (EAGGF) and amending and repealing certain Regulations	It establishes a Community framework support for sustainable rural development and includes measures to restore agricultural and forestry production potential that have been damaged by natural disasters.	recovery

Directive	Ex 1) DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy	It aims to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. The directive promotes the development of river basin management plans, along with associated programmes of measures. It superficially addresses flooding aspects (e.g. it mentions that it is necessary to mitigate the effects of floods) and considers flooding a force majeure. However, it paves the way towards a policy on flood risk management.	response and mitigation
	Ex 2) COUNCIL DIRECTIVE 1999/31/EC of 26 April 1999 on the landfill of waste Official Journal L 182 , 16/07/1999 P. 0001–0019	It aims to provide for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment of landfills and their wastes. It states that the location of a landfill must take into consideration requirements relating to floods.	prevention
	Ex 5) COUNCIL DIRECTIVE 95/498/EC of 23 November 1995 concerning the Community list of less-favoured farming areas within the meaning of Directive 75/268/EEC (Sweden), Official Journal L 287 , 30/11/1995 P. 0033 –0052	It states that farms must meet the necessary requirements to be protected against floods in Sweden.	prevention

(Continued)

Table 2. (Continued)

Type of secondary legislation	Name of secondary legislation that deals with flood-related issues to some degree	Brief description of flood-related aspect addressed	Flood risk management phase
	Ex 3) COUNCIL DIRECTIVE 95/22/EC of 22 June 1995 amending Directive 91/67/EEC concerning the animal health conditions governing the placing on the market of aquaculture animals and products, Official Journal L 243 , 11/10/1995 P. 0001–0006	It states that in order for a farm to be approved, it must meet various requirements, amongst which is that it must be protected against flooding and infiltration of water.	prevention
	Ex 4) COUNCIL DIRECTIVE 92/57/EEC of 24 June 1992 on the implementation of minimum safety and health requirements at temporary or mobile construction sites (eighth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC), Official Journal L 245 , 26/08/1992 P. 0006–0022	It lays down minimum safety and health requirements for temporary or mobile construction sites. It recommends that precautions be taken in an excavation, well, underground or tunnel...to prevent hazards entailed in case of flooding.	prevention
	Ex 6) COUNCIL DIRECTIVE 82/883/EEC of 3 December 1982 on procedures for the surveillance and monitoring of environments concerned by waste from the titanium dioxide industry, Official Journal L 378 , 31/12/1982 P. 0001–0014	It lays down the procedures for monitoring effects on the environment of the discharge, dumping, storage on, tipping on or injection into the ground of waste from the titanium dioxide industry. It states that in case of a flood or any other natural disaster, MS may derogate from it.	response

Decision	DECISION No 1600/2002/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 July 2002 laying down the Sixth Community Environment Action Programme	It establishes an EU action plan to address the environment. It promotes preparation for measures to adapt to the consequences of climate change, such as desertification and flooding. In addition, welcomes initiatives in the area of EU coordination to actions by MS in relation to accidents and natural disasters, including the organisation of public and business awareness raising schemes.	mitigation, preparedness and response
	DECISION No 1513/2002/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 June 2002 concerning the sixth framework programme of the European Community for research, technological development and demonstration activities, contributing to the creation of the European Research Area and to innovation (2002 to 2006)	It establishes a multi-annual programme for EU research, technological development and demonstration activities. One of the research priority areas is <i>desertification and natural disasters</i> . It recommends the study of environmental impact issues on health, along with research on methods for risk assessment and the mitigation of risks of natural disasters to people.	prevention and preparedness
	COUNCIL DECISION of 23 October 2001 establishing a Community mechanism to facilitate reinforced cooperation in civil protection assistance interventions (2001/792/EC, Euratom)	It establishes a Community mechanism to facilitate reinforced cooperation between the Community and the MS in civil protection assistance intervention in the event of major emergencies, or the imminent threat of an emergency.	response

(Continued)

Table 2. (Continued)

Type of secondary legislation	Name of secondary legislation that deals with flood-related issues to some degree	Brief description of flood-related aspect addressed	Flood risk management phase
	COMMISSION DECISION 94/585/EC on of 8 April 1994 concerning the grant of assistance from the cohesion financial instrument to the following stage of project in Ireland: Bray sewerage scheme (Stage II) No CF: 93/07/61/037, Official Journal L 226 , 31/08/1994 p. 0047–0055	It justifies the financial assistance from the cohesion fund for the sewer system project in Ireland is necessary to “ <i>alleviate flooding problems on the esplanade and will eliminate the storm overflow and the South Beach outfall which is a major public health hazard</i> ”.	prevention and mitigation
	COMMISSION DECISION 94/552/EC of 16 December 1993 concerning the grant of assistance from the cohesion financial instrument to a set of projects concerning erosion control and revegetation in Spain (Only the Spanish text is authentic) Official Journal L 218 , 23/08/1994 p. 0227–0235	It justifies the financial assistance from the cohesion fund for the erosion control and revegetation project in Spain. It states that “ <i>erosion control in seriously degraded areas or areas with a particular impact on flooding and requiring the following measures, in particular: reforestation of areas with less vegetation, improvement of the quantity and quality of existing vegetation and operations to stabilize torrential channels</i> ”.	mitigation
Recommendation	RECOMMENDATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2002 concerning the implementation of Integrated Coastal Zone Management in Europe (2002/413/EC)	Within the framework of integrated coastal zone management, it promotes the need to address the increased frequency of flooding, due to climate change.	mitigation

Opinion	OPINION OF THE COMMITTEE OF THE REGIONS on the 'Proposal for a Council Decision on a Civil Protection Mechanism in the event of emergencies' (2001/C 253/06)	The Committee of the Regions (CoR) promotes “to increase the development of long-term planning strategies (techniques for predicting extreme weather conditions, anti-flood systems...” along with the exchange of experience and technology.	Mitigation and preparedness
	OPINION OF THE ECONOMIC AND SOCIAL COMMITTEE on the 'Proposal for a European Parliament and Council Recommendation concerning the implementation of Integrated Coastal Zone Management in Europe' (2001/C 155/05)	The Economic and Social Committee highlights the importance of including spatial planning and land use standards when addressing flood-related issues.	Prevention and mitigation
	OPINION OF THE COMMITTEE OF THE REGIONS on the 'European Spatial Development Perspective' (1999/C 93/07)	The CoR emphasizes the need to improve flood prevention. It highlights the importance of addressing upland settlements, sustainable farming and forestry and maintenance of anti-flooding defences.	Prevention and mitigation

Table 3. Policy areas of the European Commission that address flood-related strategies

Policy area/ Flood-related strategy	Environment	Research	Civil protection	Regional	Agriculture	Forestry	Information society	Space
PRE-FLOOD								
Risk assessment	x	x						x
Monitoring	x	x		x				x
Warning	x	x					x	x
Forecasting	x	x						x
Landuse	x	x		x	x	x		
Risk communication	x	x					x	
Training		x	x	x				
Education		x	x	x				
Engineering works	x	x		x				
Ecological works	x	x		x				
SYN-FLOOD								
Crisis management		x	x				x	x
POST-FLOOD								
Relief				x	x	x		
Impact	x	x	x	x	x	x	x	x
Lessons learnt and good practice	x	x	x					

in Europe. The main policy areas where the European Commission has contributed are described below. They are also summarised in Table 3, which also portrays the flood-related strategy addressed.

3.1. Directorate General on Environment Policy (DG ENV)

Since the Cardiff Process (European Commission, 1998), which launched a strategy for integrating environment issues into EU Policies, DG ENV has started to interface with all other policies. This then led to another milestone strategy on sustainable development (European Commission, 2001), which was launched just before the Summit in Johannesburg, South Africa. These strategies have led to an increased awareness towards the environment, leading to many policy initiatives, such as those described below (only those affecting flood risk management are mentioned).

3.1.1. Civil protection policy²⁵

The activities in the field of civil protection are of three types: *prevention*, *preparedness/intervention* and *response/restoration*. Floods have been addressed in all three activities, summarised in Table 4. In addition to these, there is also an initiative launched in December 2002 on *An Integrated EU Strategy on Prevention, Preparedness and Response to Natural, Man-made and Other Risks*²⁶. A consultation of interested parties took place between 5 February and 7 April 2003 on a Working Document: “*Civil Protection: improvement of public awareness and safety in the face of natural and man-made hazards*”²⁷. Floods are one of the main hazards addressed in the document. This initiative was the result of the August 2002 floods in Central and Eastern Europe.

3.1.2. Water, marine and soil policies

An awareness raising initiative on flooding issues was launched during Green Week²⁸ 2003. This was promoted to pave the way towards investigating policy-making in the field of floods based on the existing legal basis, particularly on the Water Framework Directive (WFD), where floods are addressed several times. In the aftermath of the Summer 2002 floods and the frequent floods in Europe, the Directorate General for Environment has recently launched a policy initiative on flood risk management (European Commission, 2004).

²⁵ http://europa.eu.int/comm/environment/civil/prote/cp01_en.htm

²⁶ http://europa.eu.int/comm/environment/civil/prote/integrated_strategy_en.htm

²⁷ The document can be downloaded from:

http://europa.eu.int/comm/environment/civil/prote/consultation_en.htm

²⁸ Green Week brings people together to debate about key environmental issues of sustainable consumption and production, renewable energy & climate change and water. Green Week 2003 was held during the week that included 5 June 2003, which was the United Nations Environment Day. A session on floods entitled: *Flood prevention and flood protection - a challenge to integrated river basin management*, was given, which involved stakeholders such as companies, industry associations and non-governmental organisations, etc.

(http://europa.eu.int/comm/environment/greenweek/conference/0506_en.htm#20)

Table 4. Civil protection activities addressing flood-related issues

Type of activity	Description of activity
Prevention	Financing of flood-related projects (http://europa.eu.int/comm/environment/civil/prote/cpactiv/cpmaj01.htm)
Preparedness/intervention	New Mechanism: it aims to facilitate reinforced cooperation in civil protection assistance interventions in the event of natural, technological and environmental disasters, inside and outside the EU. It enables concrete and prompt assistance from intervention teams from EU MS' when the resources of a country are not sufficient to deal with disasters. Additionally it aims to improve interventions in case of disasters throughout Europe by a better coordination of means and the strengthening of communication and training capacities. (http://europa.eu.int/comm/environment/civil/prote/cp12_en.htm) Information to the Public: The objective is to improve the degree of self-protection of the population and to achieve progressively a common safer area for the 370 million of European citizens. (http://europa.eu.int/comm/environment/civil/prote/cpactiv/cpmaj04-01.htm#Objectives)
Response/restoration	

3.2. Directorate General on Agriculture Policy (DG AGRI)²⁹

The Common Agricultural Policy (CAP) is the most important policy in the EU, as it is almost 50% of the EU budget is allocated to it. As natural disasters pose a threat to food security, the CAP reform, which was agreed in June 2003, endeavours promote mitigation measures such as the reopening of floodplains and the development of retention areas in case of flooding, particularly in the area of sustainable rural development.

3.3. Directorate General on Regional Policy (DG REGIO)³⁰

Regional policy is about solidarity in the EU and its neighbours (European Commission, [1999]). It provides assistance to help the lesser developed regions overcome their handicaps. The financial assistance is in the form of initiatives and schemes, through four Structural Funds: European Regional Development Fund³¹ (ERDF), European Social Fund³² (ESF), European Agricultural Guidance and Guarantee Fund³³ (EAGGF) and Financial Instrument for Fisheries Guidance³⁴

²⁹ http://europa.eu.int/comm/agriculture/index_en.htm

³⁰ http://europa.eu.int/comm/regional_policy/index_en.htm

³¹ It promotes economic and social cohesion within the EU through the reduction of imbalances between regions or social groups.

³² It allows the EU to carry out strategic objectives of its employment policy.

³³ It contributes to the structural reform of the agriculture sector and to the development of rural areas.

³⁴ It contributes to the structural reform of the fisheries sector.

Table 5. Initiatives addressed by the Structural Funds that deal with flood-related issues

Initiative/ instrument	Objective 1 ¹	Objective 2 ²	Objective 3 ³	Interreg III ⁴	Urban II ⁵	Leader + ⁶
ERDF	x	x		x	x	
ESF	x	x	x			
EAGGF	x					x

¹It addresses development and structural adjustment of regions whose development is lagging behind.

²It addresses economic and social conversion of areas facing structural difficulties.

³It concerns the adaptation and the modernisation of national policies and systems of education, training and employment

⁴It aims to stimulate interregional cooperation in the EU.

⁵It promotes for sustainable development in the troubled urban districts of the European Union.

⁶It is an initiative for rural development.

(FIFG). Flood-related issues are addressed in the first three instruments. In Accession and Candidate Countries, there are similar instruments: Instrument for Structural Policies for Pre-Accession³⁵ (ISPA) and Special Accession Programme for Agriculture and Rural Development³⁶ (SAPARD). As a consequence of the summer 2002 floods, the Solidarity Fund was established (see Table 2). Table 5 shows the main initiatives carried out in the EU regional policy sector that address flood-related issues.

Another important initiative is the European Spatial Development Perspective (ESDP)³⁷. The ESDP is a spatial planning policy framework for sectoral policies of EU (e.g. floods), as it has been launched to obtain a balanced and sustainable development of the European territory. Floods affect social and economic cohesion, as experienced by many countries in Central and Eastern Europe, during the summer floods of 2002. Many flood-related projects were financed by the Structural Funds, which all contribute to the ESDP. Many of the initiatives addressing flooding issues have been preventive actions.

3.4. Directorate General on Research Policy (DG RTD)³⁸

One of the necessary and fundamental pillars of flood risk reduction is research. EU collaborative efforts of underpinning research in the field of natural disaster reduction have been promoted by DG RTD, through multi-annual research

³⁵ Instrument for regional policy for Accession and Candidate Countries.

³⁶ Programme for assistance to agricultural and rural development for Accession and Candidate Countries.

³⁷ ESDP was born on 10-11 May 1999 in Potsdam, Germany, during the Informal Council of EU Ministers responsible for Spatial Planning.

(http://europa.eu.int/comm/regional_policy/sources/docoffic/official/reports/pdf/sum_en.pdf)

³⁸ http://europa.eu.int/comm/research/index_en.cfm

framework programmes since the early 1980's (Samuels, 2003). These framework programmes (FP) facilitated collaborative research between firms, universities and research centres at EU and international level. This has continued, through strengthened political support, right through to FP6, the present framework programme. In DG RTD, it is the Directorate I on Environment that addresses flood-related issues. The section on floods within the Natural and Environmental Disaster Exchange System (NEDIES) provides a list of DG RTD funded flood projects³⁹ with direct links to the DG RTD Cordis website, which offers background information on each project.

One of the priority research themes in FP6 is sustainable development, global change and ecosystems, where *Mechanisms of desertification and natural disasters*⁴⁰ is one of the research areas addressed. An integrated project⁴¹ that needs to be highlighted is FLOODsite⁴² which has started in March 2004. FLOODsite (Integrated flood risk analysis and management methodologies) aims to provide an integrated framework for flood risk management from operational to planning time horizons (50 years and beyond) in sustainable pre-flood measures (infrastructure provision, planning and vulnerability reduction); flood event management (early warning, evacuation and emergency response); and post-event activities (review and regeneration). It is the biggest EC research project on floods, which is envisaged to take 5 years to complete. There are 36 partners involved in this 10 Million-Euro project.

3.5. Directorate General of the Joint Research Centre (DG JRC)⁴³

Another Directorate General that addresses research on flood-related issues is the European Commission Joint Research Centre. DG JRC is a *research based support centre*, which provides independent scientific and technical advice to the Commission and its policy-making Directorates-General (DGs), as well as the Council, European Parliament (EP) and MS. There are two Actions in the JRC that address flood-related issues: Weather-Driven Natural hazards (WDNH) and Natural and Environmental Disaster Information Exchange System (NEDIES), which are briefly described below.

³⁹ http://nedies.jrc.it/pag_disasters.asp?Sezione=1&idSez1=601&idSez2=602&idSez3=603&idSez4=604&idMenu=Floods

⁴⁰ <http://www.cordis.lu/sustdev/environment/ecosystems.htm>

⁴¹ An integrated project is a new research instrument launched in FP6. It is a multi-partner project which aims to support objective-driven research, where the primary deliverable is knowledge for new products, processes, services, etc. They should bring together a critical mass of resources to reach ambitious goals aimed at either increasing EU competitiveness or at addressing major societal needs. (http://www.cordis.lu/fp6/instr_ip.htm)

⁴² <http://www.floodsite.net>

⁴³ <http://www.jrc.cec.eu.int>

3.5.1. *LISFLOOD and the Weather-Driven Natural Hazards (WDNH)*⁴⁴

WDNH is a JRC action that provides scientific support towards the development and real time testing of a pre- operational pan-European flood forecasting system with 1 to 10 day lead-time, focusing on major trans-national river basins. Furthermore, it evaluates flood defense and mitigation plans in major European trans- national drainage basin through scenario modelling of the effects of engineering measures, land-use change including regional development (e.g. urban expansion) and climate change effects on flood risk. This will be carried out by a flood modelling system called LISFLOOD, which was developed by the Joint Research Centre of the European Commission. The model simulates floods in large European drainage basins. Unlike most other hydrological models – such as MIKE-SHE, TOPMODEL or HBV –, it is capable of simulating large areas, while still maintaining a high resolution, proper flood routing methods and physical process descriptions. LISFLOOD is also especially designed to simulate the effects of change in a easy and realistic way: land-use changes, modifications of the river geometry, water reservoirs, retention areas and effects of climate change. LISFLOOD is embedded in a GIS and is using readily available European datasets, such as Corine Land Cover, the European Soils Database, and the 1km resolution European Flow Network. LISFLOOD simulates the hydrological processes at the surface, in the soil, and in the river channel network on a regular horizontal grid, usually using a high resolution compared to the catchment size: LISFLOOD can easily handle 100,000 grids or more. Using LISFLOOD, scenario studies have already been carried out for the Oder (De Roo & Schmuck, 2002, De Roo et al 2003a) and Meuse basin, and studies are ongoing in the Elbe and Danube, in support of several EU/EC initiatives (6th Environmental Action program, ESDP and ESPON initiative of DG REGIO).

Apart from scenario studies, the LISFLOOD model is used in the development of a European Flood Alert System, started following. Following the guidelines of the Secretariat- General (SEC(2002)907/2) and a communication from the Commission about ‘The Community response to the flooding in Austria, Germany and several Applicant countries’ (COM (2002)481 final). This supports also several other EU/EC initiatives such as the 2nd Community Action Program on Civil protection and the Establishment of the Monitoring and Information Centre (MIC) at DG ENV.

The European Flood Alert System (EFAS) combines state-of-the-art expertise in meteorology and hydrology on European scale. The aim of EFAS is to provide a pre-warning for floods to national services responsible for forecasting and warning, with a maximum leadtime of 10-days, depending on the reliability of the weather forecast. This medium-range leadtime goes beyond the typical 1-2 leadtime of national systems. The system runs on 5km for the whole of Europe and on 1km for selected test catchments. In addition, information on the uncertainty of the prediction is incorporated. A feasibility study for EFAS (De Roo et al 2003b) has been performed within the EDFS shared cost action funded by DG-RESEARCH,

⁴⁴ <http://ies.jrc.cec.eu.int/Actions/WDNH>

with partners from leading Meteorological Services (ECMWF, DMI, DWD), hydrological institutions (RIZA, SHMI, Delft Hydraulics, GRDC), and research institutes (University of Bologna, Bristol University, Lancaster University) across Europe.

3.5.2. *Natural and Environmental Disaster Information Exchange System (NEDIES)*⁴⁵

The NEDIES project aims to disseminate lessons learnt from disasters and promotes exchange of good practice amongst disaster risk managers. NEDIES activities consist of organisation of targeted workshops and expert meetings promoting dialogue amongst stakeholders in the field of disaster risk management; preparation of lessons learnt reports, guidance documents and proceedings; support to policy-making Directorates General, particularly DG Environment; support to MS by providing them with information required. In 2003, two new activities were launched: *socio-economic aspects of disasters* and *natech (natural hazard triggering technological disaster) risk analysis*. The second activity is part of a multi-annual research collaboration agreement with the United Nations International Strategy for Disaster Reduction⁴⁶

NEDIES has produced two documents on floods: *Lessons Learnt from Flood Disasters* (Colombo and Vetere Arellano, 2002b) and *Guidelines on Flash Flood Prevention and Mitigation* (Colombo et al., 2002). Furthermore, the NEDIES system offers 19 disaster forms addressing floods.

3.6. Directorate General on Information Society Policy (DG INFSO)

In line with the Lisbon Strategy⁴⁷ “to make Europe the world’s “the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion” (European Commission, 2000b; European Commission, 2003a), one of the priority themes addressed with view to Information Society Technologies (IST) is risk management. The objective is to develop open platforms, integrated systems and components towards an improved risk management by fostering a European info-structure and service platforms which will facilitate the use of interoperable components and sub-systems, which could feed into building risk management community. Flood risk management would benefit from this initiative as it involves the participation of major public and private interested stakeholders.

⁴⁵ <http://nedies.jrc.it>; <http://natural-hazards.jrc.it>

⁴⁶ <http://www.unisdr.org>

⁴⁷ In March 2000, the Lisbon European Council launched a 10-year strategy for economic, social and environmental renewal. (http://europa.eu.int/comm/lisbon_strategy/index_en.html)

3.7. ECHO – European Office for Emergency Humanitarian Aid⁴⁸

Action by the European Commission in this area is based on the EU's humanitarian aid policy⁴⁹. The aim is to provide help to victims of all types of disasters, including floods, by means of providing resources and services or by promoting preventive measures, including those to counter floods. This assistance is mainly geared towards vulnerable people, particularly those of developing countries.

3.8. Other Initiatives at EU Level

3.8.1. *Infrastructure for Spatial Information in Europe (INSPIRE)*⁵⁰

This initiative aims at making available relevant, harmonised and quality geographic information to support formulation, implementation, monitoring and evaluation of EU policies with a territorial dimension or impact. 17 themes have been identified, many of which are directly or indirectly related to flood risk management on a territory (natural and technological risks, hydrography, land regulation, elevation, geophysical environment, etc.).

3.8.2. *Global Monitoring for Environment and Security (GMES)*⁵¹

It is a joint initiative of the European Commission and the European Space Agency to bring data and information providers together with users, as to better understand each other and agree on how to make environmental information available to the people who need it. A second specific goal is the creation of a 'European Shared Information System' for exchanging of a wide range of useful information on environment and security matters. All the priority themes⁵² addressed in GMES are very important for flood risk management.

3.8.3. *Galileo*⁵³

Galileo will provide the first satellite positioning and navigation system specifically for civil purposes. Relevant territorial risk management applications are: environment management, crisis management, search and rescue, monitoring of intermodal transport of hazardous goods, etc., which could all directly or indirectly contribute towards improving flood risk management.

⁴⁸ http://europa.eu.int/comm/echo/index_en.htm

⁴⁹ Council Regulation (EC) No 1257/96 of 20 June 1996

⁵⁰ <http://inspire.jrc.it>

⁵¹ http://europa.eu.int/comm/space/prog/gmes/gmes_en.html

⁵² There are 9 thematic priorities: land cover change in Europe, environmental stress in Europe, global vegetation monitoring, global ocean monitoring, support to regional development aid, systems for risk management, systems for crisis management and humanitarian aid and information management tools and contribution to the development of a European spatial data infrastructure. (<http://www.gmes.info/projects/index-them.html>)

⁵³ http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm

4. IDENTIFIED NEEDS IN FLOOD RISK MANAGEMENT AT EU LEVEL

The CEC has many initiatives addressing flood risk, but there is still a lot that can be done at EU-level that could complement and provide added-value to flood risk management practice in MS. Taking stock of ongoing EU level initiatives and European flood risk management practice, whilst respecting the Principle of Subsidiarity⁵⁴ the following needs have been identified, followed by a proposed way forward (*in italics*), and the potential benefit (*in underlined italics*).

- The *acquis communautaire* tends to address the threat of flooding in various sectors as a force majeure situation, thus dealing with them as an act of God, e.g. if there is a flood, the legal requirements are no longer valid. An example of this is the case for the Council Directive 82/883/EEC and Directive 2000/60/EC of the European Parliament and of the Council (see Table II). Thus, floods should no longer be addressed as an act of God.

*The CEC should set up a revision mechanism at regular intervals that identifies all EU legal acts addressing floods as an act of God, followed by their prioritisation. Also policies that address floods to some degree should be regularly checked, revised and updated, so as to keep up with the changes that occur in society (particularly those addressed by the Lisbon Strategy and Sustainable Development Strategy of the EU). In partnership with the MS, the CEC should propose changes that incorporate mitigation aspects. These would then be submitted to the EP and Council for consideration. This is in line with the general process of updating of the *acquis* (European Commission, 2003a). This mechanism would also facilitate the passing of new legislation that could assist in improving flood risk management on a territory. This should be carried out on a case-by-case situation.*

This would result in a shift from a response-driven approach to a prevention/mitigation approach in dealing with floods.

- A coordinated effort in enforcing sustainable floodplain management on the EU territory is needed. The Water Framework Directive clearly sets the stage for such an initiative, as it promotes an integrated river basin management (IRBM). However, it fails to address flood risk management in a coordinated, sustainable and effective manner, as it focuses more on water quality and water use, whilst

⁵⁴ The subsidiarity principle is intended to ensure that decisions are taken as closely as possible to the citizen and that constant checks are made as to whether action at Community level is justified in the light of the possibilities available at national, regional or local level. Specifically, it is the principle whereby the Union does not take action (except in the areas which fall within its exclusive competence) unless it is more effective than action taken at national, regional or local level. It is closely bound up with the principles of proportionality and necessity, which require that any action by the Union should not go beyond what is necessary to achieve the objectives of the Treaty. (<http://europa.eu.int/scadplus/leg/en/cig/g4000s.htm#s10>)

addressing the importance of ecosystems aspects. Although floods are addressed seven times in the directive, clearer guidelines are needed to improve flood risk management.

(i) *The CEC should work together with regional and local administrations in offering assistance to national governments in providing input for a set of accepted guidelines on flood risk management on the floodplain. This process has already started through the launching of the Communication on flood risk management (European Commission, 2004).*

This would assist in enhancing better cooperation at various levels and better identifying who does what.

(ii) *The CEC should assist MS in increasing the momentum of the raising awareness of the public, policy-makers and decision-takers to the importance of floodplain management and the medium- and long-term benefits of promoting sustainable development on the floodplain. The Science and Society Action Plan is a step in the right direction, but it needs reinforcing.*

This would contribute towards ensuring that the various differences and similarities regarding flood-related matters across the EU are well communicated and reach all the stakeholders.

(iii) *The CEC start mainstreaming flood risk issues in its various sectoral policies (Environment, Agriculture, Regional Planning, etc.).*

This would contribute significantly to raising awareness on flood risk issues.

- There is a need to better address natech⁵⁵ aspect of floods. This has been indirectly touched in the Council Directive 82/883/EEC, which describes the procedures for the surveillance and monitoring of effects on the environment of discharge, dumping, storage on, tipping on or injection into the ground of waste from the titanium dioxide industry. Article 8 states that in case of flooding, the directive was no longer applicable. The potential spatial and temporal effects of floods need to be addressed in relation to industrial establishments. In the WFD, it has been addressed more directly, but does not give in depth guidance. Lastly, the Seveso II Directive⁵⁶ also indirectly addresses natechs: (Section IV of Annex II, Article 8, Article 12).

(i) *The CEC should facilitate the establishment of a mechanism to collect information on natech events, where spatial and temporal systemic aspects are addressed. This practice is carried out in some countries, but it is not done in a systematic manner (Vetere Arellano et al., 2004; Cruz et al., 2004).*

By establishing a systematic collection mechanism, CEC will be able to assist MS to better monitor potential systemic risks on the territory.

⁵⁵ Natech is a natural hazard that triggers a technological disaster (e.g. a flood that causes a chemical plant leakage into the environment)

⁵⁶ Seveso II Directive (98/82/EC) aims “to prevent major accidents which involve dangerous substances, and to limit their consequences for man and the environment with a view to ensuring high levels of protection throughout the Community in a consistent and effective manner.”

(ii) *Technological installations on the floodplain should be identified and specific guidelines should be prepared to help communities cope best with the threat of a natech event.*

This too, if carried out in a systematic manner (e.g. via databases), would lead to better risk management of the secondary effects of flooding (domino effects).

(iii) *An awareness raising campaign should be launched in order to make the public and the decision-takers better understand the importance addressing the threat of a natech hazard, which can have medium- to long-term effects (e.g. Baia Mare, Spolana) on the environment and the health of citizens.*

People tend to focus on the effects of the flood in the short-term, however, this would allow people to better understand the potential longer-term effects of flooding.

- Need to promote a systematic collection of data and interoperability of databases for improving European knowledge base (best/good practice and lessons learnt).
(i) *Specific guidelines should be provided for collecting information on floods, based on already existing templates. Countries should endorse such a systematic collection of data in order to better analyse them. More focus should be given to data on vulnerability (e.g. critical infrastructure that can cause damage, if a flood were to affect it, along with medium to long-term damages to the environment and population) and resilience (e.g. number of firemen for every citizen in a given area) parameters related to floods. These types of information require the type of monitoring as that given to hazard-related data (e.g. rainfall).*

This would lead to having better analyses (risk and scenario building), as more targeted data would be available. Thus, decision-takers will be better assisted when decisions are required to be taken.

(ii) *Instead of creating a new European-wide database, it would be useful to establish the interoperability amongst already existing databases. Some form of institutional mechanism should facilitate this.*

This would ensure that the existing technology addressing interoperability can be used by the end-users, facilitating exchange of flood-related information.

(iii) *It would be useful to build on the existing NEDIES system, with view to the collection of lessons learned from flood risk management, as it is presently the only repository of lessons learnt in Europe. It also could potentially become a very useful knowledge base on lessons learned for input into risk assessment and management practice. Also, it addresses many types of risks and offers the possibility of a cross-fertilisation approach to the analysis of lessons learned, providing a useful source for multi-disciplinary research in the field of disaster risk management.*

The NEDIES system would become the reference point of lessons learned from disasters, facilitating the exchange of good practices amongst MS in the 21 official languages of the EU.

- Although insurance companies have long analysed insurance losses with view to flooding, these losses are generally much lower than economic damage. There is a need to better address damages.

(i) *The CEC, MS and the insurance industry should increase dialogue amongst themselves in addressing flood insurance issues. A burden-sharing mechanism should be established that targets investment in mitigation schemes launched by governments, with support from the CEC, to assist people living on the floodplain (e.g. if the household complies to such schemes and invests in flood-proofing initiatives, then their insurance premiums should decrease).*

MS that invest in mitigation schemes would benefit more.

(ii) *Information should be shared between governments and insurance industries in order to better monitor and analyse socio-economic impacts (direct and indirect; tangible and intangible; reversible and irreversible).*

This would assist in better developing criteria for allocation of post-disaster resources.

(iii) *The EU Solidarity Fund should be transformed into a financial assistance that promotes sustainable development on the floodplain, by ensuring that mitigation measures are implemented. It should go further than just compensation. Compensation should be based on prevention/mitigation criteria. For example, investment in flood prevention/mitigation measures (structural and non-structural) with respect to the Gross National Product could be one indicator.*

Those countries that have made efforts to implement prevention/mitigation strategies should benefit more from the Solidarity Fund. This would not be a harmonisation process, as it respects each country's administrative processes and disaster imprinting. However, those who make more efforts in mitigation schemes will be more favoured than those who do it less, or do not do it at all.

- It is necessary to strengthen the flood risk management community so as to be able to obtain better representation in policy-making related arenas in sectors that affect flood risk management, also, so that duplication of work is minimized, practitioners should know who's who in the field.

A coordination mechanism should be set up to build momentum created by the networking and collaborative efforts promoted by the CEC (Framework Programmes, Action Plans, Regional Development, etc.). This is already happening in the various CEC-funded research instruments such as Integrated Projects, Network of Excellences, etc., where researchers, end-users and industry are working together towards progressing in the field of research. Although European cooperation is a success, there is still a need to build momentum in mainstreaming research and user needs in policy-making in a coordinated manner. The CEC may provide that at EU level through targeting information amongst actors in the field of risk management. In addition, the timing of projects should also be taken into account. Sometimes, the results of one project may be useful for the progress of another, but the latter may obtain the results of the former, at a stage when the project of the latter is ending. Thus, a better coordination of project launches, according to project plans should be ensured. The risk community would start having a stronger voice in the policy-making arena.

- There is a need to address the needs of practitioners and ensure that potential users of potential research outputs (tools, services, etc.) are continuously informed about advances in technology in order to facilitate possible institutionalization and operationalisation of results.

This should be addressed in the coordination mechanism toward strengthening the flood risk management community (see previous bullet).

This would lead to a more efficient channelling of research results being utilised by end-users.

- It is necessary to increase targeted awareness raising initiatives on flooding issues (public, decision-takers, businesses, etc.).

The CEC should facilitate this process by means of the various existing programmes (e.g. Science and Society, Risk Governance, etc.)

This would lead to an improved flood risk perception, and thus would assist in improving risk management. Many flood-related problems are due to risk communication issues.

5. A PROPOSED VISION OF FLOOD RISK MANAGEMENT AT EU LEVEL

In the EU's quest to become the most competitive and dynamic knowledge-based economy in the world, there is a need to address threats, such as floods, that may hamper progress towards this goal. Floods have been known to cause disruption on the territory with multi-fold consequences that do not stop in the immediate aftermath of the flooding, but tend to propagate in time.

To address the above, the proposed **vision** of a possible European Union is: *where a fortified multi-disciplinary approach to flood risk management is implemented, where flood risk actors collaborate with each other via processes that are engraved in institutional frameworks that facilitate and enhance collaboration (particularly in monitoring, collecting, analysing and disseminating flood-related data). This multi-disciplinary approach has permeated all sectors: research, industry, policy-making, decision-taking, etc. at all levels: local, regional, national and European, not to mention international. It is an EU where the overlapping of efforts are reduced to the minimum, and thus risk management practice is optimised, because actors are aware of what the others are doing in the field. In addition, it is where risk management practitioners have shifted from focusing on the hazard component of risk to the evolving inter-relationship between the physical phenomenon, technology and society, i.e. dynamic vulnerability assessment, building on lessons learned through post-disaster analysis and foresight studies, which have been mainstreamed into common risk management practice. The public's perception of flood risk is well understood by policy-makers, and thus, flood risk policies are better targeted and better communicated to the citizens. Facilitating mechanisms have been established to mainstream lessons learned from flood events that are shared amongst stakeholders via interoperable databases and information systems. All these are*

contributing to minimising the impacts of floods (i.e. less human and environmental consequences and minimised socio-economic damages) and promoting a sustainable flood risk management practice (efficient management and allocation of limited resources). The above-proposed vision would indeed benefit the EU citizens, particularly those who reside in and who visit flood-prone areas.

The challenges ahead are (i) to ensure that the above-identified needs are addressed, (ii) to take on board the possible ways forward proposed and (iii) to transform the proposed vision into reality using a participatory process and cooperation amongst researchers, flood risk managers, policy-makers, decision-takers, the public, etc..

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CHAPTER 24

ON THE FLOOD RISK IN THE NETHERLANDS

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Abstract: The Netherlands are protected from storm surges and river floods by the Deltaworks: a reinforcement of the primary flood defence system consisting of coastal dunes, dikes and storm-surge barriers. These were implemented in response to the dramatic flooding disaster in 1953. Over the last 50 years, billions of euros have been invested in this scheme creating a feeling of safety in society. However, in this paper we argue that the current sense of safety may be inappropriate. Scientific evidence is growing, which shows that the hydraulic baseline conditions like storm wave properties and maximum river discharges may be different and more severe than recently thought. Climate change and sea-level rise may aggravate this situation. Moreover, the number of people and the value of properties behind the dikes have increased significantly since the coastal protection schemes were designed. In the present situation the flood risk appears to be disproportionately large compared to other daily risks. We conclude that on the short term the existing coastal and river flood protection should be reinforced to accommodate the more extreme hydraulic conditions and protect these valuables. Alternatively, protection levels of different areas should be reconsidered and perhaps reduced. The latter would in fact mean retreat from particular areas

Keywords: climate change, dikes, flooding, flood protection policies, safety level, storm surge, The Netherlands

1. INTRODUCTION

1.1. Historical Flooding and the Impact on Flood Management Policy

During the past 2000 years Dutch society has learned to live with the threat of flooding. The threat of flooding has shaped the Dutch landscape and the countries' administration. Until 1000 years ago, many parts of the western half of The Netherlands were still located above sea-level. The geomorphology consisted of

peat lands behind coastal barriers and dunes. The early inhabitants settled on the higher areas along the rivers or they built dwelling mounts. Increasingly more areas “subsided” below sea-level, because of the exploitation of the peat, the construction of dikes and the reclamation of land from low lying areas and lakes and subsequent lowering of water tables. The subsidence of the land (approximately 10 centimetres per century) and sea-level rise (approximately 11 centimetres per century) has certainly contributed to this. Floods were commonplace due to the low-lying nature of the land (Table II). Particularly widespread and frequent flooding of rivers occurred during the period 1350 to 1700, according to a study by Tol and Langen (2000). Often, new dike construction was implemented after a large flood had struck. After the flood of 1916, the central government decided to build the *Afsluitdijk* in order to close the *Zuiderzee*. The plan to close the sea originated in 1667, but a law to execute the plans was only put into force after the flood in 1918. After the storm surge disaster in February 1953 the plans for the Deltaworks were made and executed.

1.2. Flooding Frequency Levels

Currently, The Netherlands are divided into so-called dike ring areas with each having a particular safety level, set according to the Flood Protection Act (*Wet op de Waterkering*, Stb, 1996). The different areas and their safety levels are depicted in Figure II. The primary flood defences of the large dike ring areas in the western part of the country, such as those of the provinces of North and South Holland, have been designed and constructed with the aim to withstand a water level that occurs once in every 10,000 years. For other, less populated, dike ring areas, such as those of the provinces of Friesland, Groningen and Zeeland, this standard is set at a lower level. The standard there is such that a particular water level that occurs once in every 4000 years can be withstood. For the dike ring areas along the rivers (Rhine, Meuse and IJssel), where high river discharges can be foreseen a few days

Table 1. Some large floods in The Netherlands. (Source: Van de Ven, 1996)

Flooding:	Date	Impact
Second Saint Elisabeth Flood	1421	More than 2000 casualties reported, the <i>Biesbosch</i> tidal area is formed
All Souls Flood	2 November 1532	
Second All Saints Flood	4–5 November 1675	
Flood	26 January 1682	
Flood	January 1916	In particular the area around the <i>Zuiderzee</i> is flooded
Storm surge disaster	31 January–1 February 1953	The water reaches an unprecedented level of 4.55 meter above Amsterdam Ordnance Datum (NAP) and there are 1835 casualties. A total of 141,000 hectares of land are flooded.

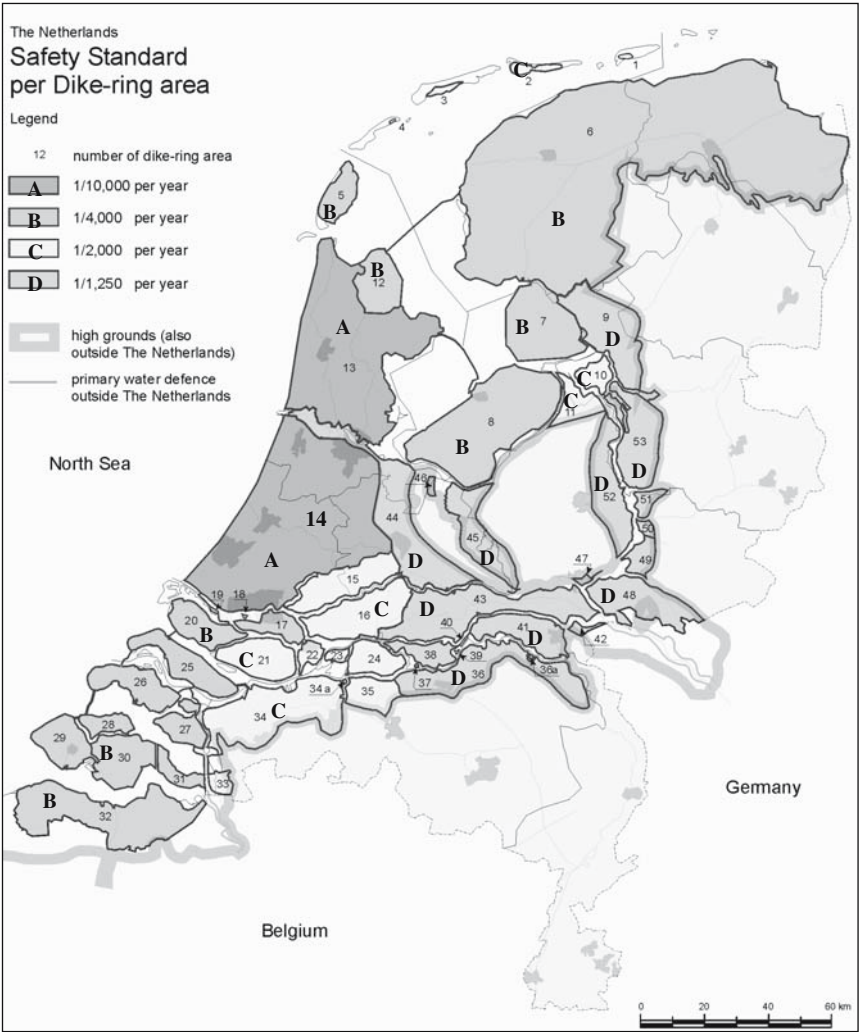


Figure 1. Safety levels per dike ring area in The Netherlands. (Source: TAW, 2000)

in advance, the “design discharges” are the critical factors in design. The dikes have been constructed up such a level that a discharge that occurs once in every 1250 years (or 2000 years in some areas) can be safely accommodated. However, not only the dike level is an important factor, but also the strength of dikes and sea walls and their resistance to different failure modes, such as sliding of the inner or outer dike slope; erosion of the dike revetment; and piping, causing water to flow under the dike and erode the dike body (TAW, 2000).

The current design requirements, however have been set according to dike heights only, in line with the earlier developed philosophy of the Delta Plan (1956). The value of human lives and property was taken into account when this Delta plan was developed. According to [Van Dantzig \(1956\)](#), the optimal investment in safety can be derived from value of human lives and property that is being protected by the Delta works. On the basis of the value that was present in the 1950s in Central Holland (dike ring 14), which includes the cities of Amsterdam and Rotterdam, the economically optimal protection from flooding was found for a sea-level that occurs once every 125,000 years. Ultimately, the level of flooding once in every 10,000 years was based on the assumption that a dike, which is designed to withstand a water level with a recurrence interval of 10,000 years, possibly fails only at a water level with a recurrence interval of 100,000 years ([TAW, 2000](#), p. 11). Apart from this, somewhat arbitrary set of assumptions, the values that are being protected today are not the same as the ones in the 1950s. The number of people that is living below sea-level in The Netherlands currently amounts to more than 8 million people, which is approximately half of the national population. The GDP in The Netherlands roughly increased five-fold over the same period. These notions make us realise that a higher safety level in Central Holland, for example being able to withstand flood levels with a frequency of occurrence of once every 1,000,000 years, is more likely to be “economically optimal”. The current 10,000-year level at least appears to be outdated and a higher level of safety is likely to be justified given the number of people at risk and the property that is to be protected.

Moreover, in view of climate change we should ask ourselves, can the present (or improved) level of safety be maintained? How can we adapt to anticipated climate change and sea-level rise and maintain an adequate safety level? And what are the consequences if we don’t succeed? What is the risk of loss of life due to flooding as compared to other environmental risks? In the following sections we will first introduce and discuss the hydraulic design conditions of the Dutch flood defence system. Secondly, we discuss the potential consequences of a failure of the primary flood defence system. Thirdly, we discuss the potential impact from climate change. Fourthly, we compare the risk of flooding with other risks. Finally, we discuss the implications of all this and come to a number of conclusions.

2. CONTEMPORARY HYDRAULIC BASELINE CONDITIONS

2.1. Compliance with Current Standards

For the maintenance of the safety level the Ministry of Transport, Public Works and Water Management has put in place a chain of procedures. These procedures include the setting of hydraulic standards (every 5 years), the checking of the flood defence system against these standards and finally the technical improvement of the flood defence system. The Technical Advisory Committee on Flood Defence (TAW) was installed after the flooding of a polder in 1965. A critical assessment of

safety levels by the TAW revealed that 50 years after the 1953 storm surge disaster the Dutch coastal defence system does not fully meet the safety levels as set out in the Flood Protection Act. The latest verification round was completed recently, using the hydraulic standards that were set in 2001 (DWW, 2002a). In 2003, the state secretary of Water Management concludes in her letter to the parliament that 549 kilometres of dikes (15% of the total length of the flood defence system) are not up to standard. And for 1217 kilometres of dikes (35%) no final judgement can be made (DWW, 2003) mainly due to the lack of information. A large part of these dikes are located behind the *Afsluitdijk* around the *IJsselmeer* area (Figure 2). However, other stretches of dikes that do not meet the standards are located along the North Sea coast of the provinces of North and South Holland and Zeeland.

2.2. Recent Insights in the Hydraulic Conditions

Evidence is mounting that the hydraulic design conditions on which the Flood Protection Act is based are to some extent inaccurate. New measurements and additional modelling has revealed that the North Sea wave period is larger than originally estimated. The waves that are likely to occur during a one in 10,000 year storm surge are considerably more powerful than assumed in the original design. Observations of waves during storms on the North Sea and recalculations for the coast indicate that the wave period (T_s) is almost 14 seconds at Hook of Holland, and at other locations almost 17 seconds, instead of the original hydraulic “design” conditions set at 12 seconds (see Table 2). As the newly estimated wave periods are about 3 seconds longer than the original ones, wave loads and wave surge could be more severe than initially anticipated. This implies that important parts of the Dutch coast would no longer comply with the safety levels set by law. These critical parts are indicated in Figure 3.

Apart from these new insights in the wave climate on the North Sea, the frequency of occurrence of extreme storm surges should be reviewed. For Hook of Holland (south-west Netherlands) this frequency has been determined by using the record of annual maximum North Sea water levels of the past 112 years. The record covers the period 1888 up to 1999, of which the storm surge in 1953 has set the maximum water level. By establishing a relationship between water level and return period, extreme levels beyond these 112 years can be estimated. Using the Gumbel distribution, the water level that is exceeded every 10,000 years at Hook of Holland was found to be approximately 5 metres above Amsterdam Ordnance Datum (NAP). The storm surge level of 1953 in this way is found to be occurring roughly once every 400 years. However, the extrapolation of frequencies up to 10,000 year on the basis of a record of 112 years is likely to lead to uncertainties. A once in 50-year event can be reasonably estimated from a record of 50 years. But the event of 1953 could have a recurrence interval of 112 years, or much higher, i.e. 1000 years. Different distributions may also lead to slightly different estimations of the one in 10,000-year water level.

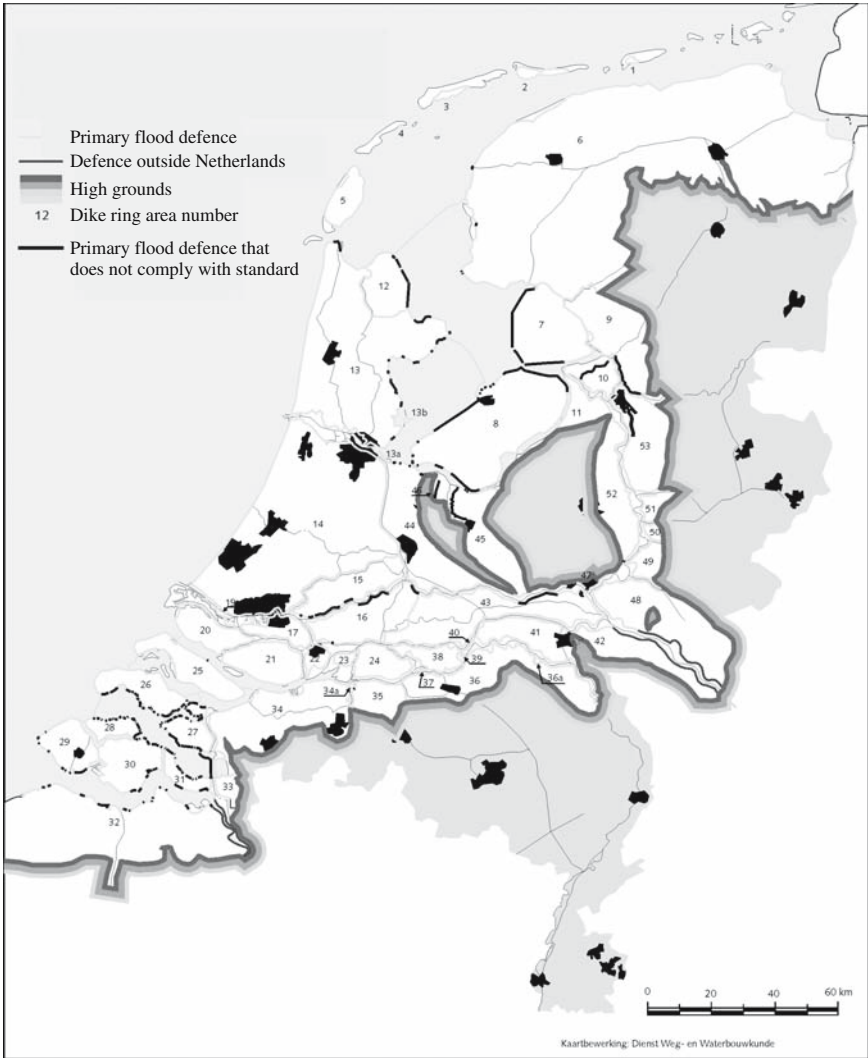


Figure 2. Primary flood defences that do not comply with the hydraulic conditions. (Source: [DWW, 2003](#))

Recently, a modelling study into the storm surge conditions on the North Sea has been performed by [Van den Brink et al \(2003\)](#). This modelling study shows the application of another approach to assessing the frequencies of occurrence of extreme storm surges and their water levels. The outcomes indicate that, although the estimate using the Gumbel distribution does not need to be discarded, the current estimate of the water level of extreme storm surges involves significant uncertainty. The storm surge level that occurs once every 10,000 years could be either lower

Table 2. Hydraulic conditions along the Dutch dune coast, original and new estimates for wave height (H_s , in metres) and the wave period (T_p , in seconds). (Source: [RIKZ, 2003](#))

Location		Original design			New estimates	
		Level (m +NAP)	Wave load H_s (m)	T_p (s)	Wave load H_s (m)	T_p (s)
North	Den Helder	4.90	9.45	12	9.60	16.9
	Callantsoog	4.99	9.40	12	9.50	16.8
	IJmuiden	5.70	8.50	12	9.05	15.6
	Scheveningen	5.75	8.60	12	8.60	14.4
South	Hook of Holland	5.60	8.40	12	8.40	13.7

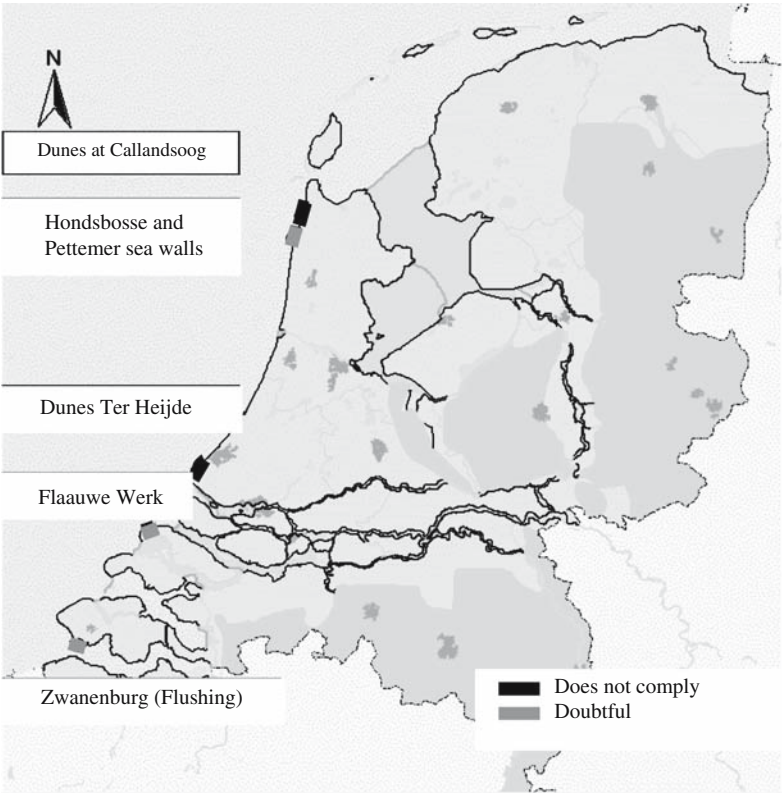


Figure 3. Flood defences that do not comply with the safety levels under increased wave load. (Source: [DWW, 2002b](#))

or higher. This estimate, however, is an important basis of the Delta plan. The research also indicates that small changes in the storm climate on the North Sea do have important consequences for coastal safety levels. Changes in storm tracks because of climate variability are at least as important as the more slowly processes of sea-level rise and land subsidence. While sea-level rise can be observed and incorporated in safety planning, storm surges may well surprise us.

Summarising: the implementation of the Delta plan has not yet been finalised, while simultaneously it has been discovered the wave climate of the North Sea is more severe than previously thought. Additionally, the calculation of the frequency of severe storm surges is disputable, or at least uncertain. This means that the risk of flooding for the present coastal defence system could be larger than laid down in the Flood Protection Act. An important aspect of future flood risks is whether storminess would increase, decrease or become more variable.

3. THE IMPACT OF A LARGE-SCALE FLOODING EVENT

The hydraulic standards of coastal and river protection, the consequent ability to withstand certain water levels (including different failure mechanisms), together with the frequency of exceedance of certain water levels as a result of storm surges and peak river discharges, determine the safety of the dike ring areas. But what will happen if a storm surge or flood wave on the river Rhine would rise well beyond the hydraulic design or if a dike would fail? Until recently, little research has been carried out into the consequences of dike failure in The Netherlands. While executing the Delta Plan (from ~1960 to present), the main concern of the Ministry of Transport, Public Works and Water Management was the reinforcement of the flood defence system. Research into the potential damages due to large-scale flooding or the adoption of an emergency plan did not fit in the pursuit for high safety levels.

A study into the potential number of casualties as a consequence of a river flood was recently published by Asselman and Jonkman (2003). They introduce a scenario in which a dike breach along the river Lek just east of Rotterdam would lead to flooding in the dike ring area of Central Holland (dike ring area 14 in Figure II). In a worst-case scenario, without evacuation, the flood wave would lead to many tens of thousands of casualties within 24 hours after the breach, estimates range between approximately 71,000 and 85,000 persons. Exactly in the low-lying areas of Central Holland (3 to almost 7 metres below NAP) many new cities have been built over the last decades. The research by Asselman and Jonkman illustrates that the land would be so rapidly flooded that evacuation routes for some areas would quickly be submerged.

Currently, a project is being executed that aims at establishing the risk for individual dike ring area, including different failure mechanisms for individual stretches of dikes and the values at risk (*Veiligheid Nederland in Kaart*, <http://www.projectvnl.nl>). Simultaneously, new research projects have recently been started into costs-benefit analyses of proposed measures for reducing the

occurrence of flooding along the rivers. Newly developed governmental plans focus on the creation of water buffering space in the former floodplain areas. These plans were described in the policy document for Water Management in the Twenty-first Century (WB21 report, [Tielrooy, 2000](#)), consisting of the improvement of water storage, water retention and accelerated discharge in order to prevent floods. The Netherlands Bureau for Economic Policy Analysis (CPB) and the Ministry of Transport, Public Works and Water Management have jointly initiated the project into the costs and benefits of flood defence measures. The benefits would be the reduction of the risk of flooding (less damage), while the costs would be the reinforcement and heightening of dikes and the creation of buffering space.

On the basis of the above, it appears to be justified to reconsider the current philosophy of safety and the safety regime of the Flood Protection Act. In order to be able to revise the philosophy and the safety regime, the risk of drowning, including emergency escape routes, and the value of the protected property need to be assessed. The projects mentioned above are first steps in this process. Next, the safety level per dike ring area can be established on the basis of the required investments in the flood defence. However, a comparison with other (non-flooding) risks in the same areas is then also warranted, in order to be able to arrive at an integrated appraisal of different risks, their spatial distribution, their potential economic and social context and the costs of risk mitigation.

4. COMPARISON WITH OTHER RISKS

How can we compare the risk of flooding and subsequent casualties with other environmental risks, such as chemical accidents, plane accidents and so on? An analysis of literature and recent policy documents gives rather diverse and often incomparable estimates for various risks. Many safety levels have been set or adjusted immediately after disasters or near-disasters. At those moments, so it seems, society is most willing to invest. The Delta plan, but also the plans for more space for the rivers after the near flood events of 1995 and 1993, originated in this way. Important questions are how the safety levels of different types of environmental risks have been established; how they relate to each other and to what extent these historically evolved levels can be evaluated as adequate.

In practice it has become clear that it is very difficult, if not impossible to develop a general applicable level for individual risk, group risk and geographically determined risks. The origin of the risk and the character of exposure are quantities that are crucial and at the same time difficult to assess. A recent study by two government advisory counsels into the geographically determined (local) risks in The Netherlands concluded that the diversity of perceptions and opinions regarding safety and the spatial diversity of the country need to be addressed (RVWS and VROM-R, [2003](#)). This can lead, however, to a situation in which public perception is more valued than quantitative risk assessment.

The study mentioned above has reported a number of risks that are listed in Table [3](#). The value for the risk of failure of the Delta works originates from a paper

Table 3. Activities and annual chance of fatality. (Source: [RVWS and VROM-R, 2003](#); originally from [Turkenburg, 1974](#))

Activity	Annual chance
<i>Voluntary risks</i>	
Suicide	1 in 10,000
Traffic accidents	1 in 4,000
Smoking	1 in 2,000
<i>Involuntary risks</i>	
Delta works	1 in 10,000,000
Lightning	1 in 2,500,000
Natural disasters	1 in 500,000
Food poisoning	1 in 125,000
Drowning	1 in 333,000
Natural radiation	1 in 50,000
All diseases	1 in 100

on nuclear safety by Turkenburg published in 1974. The risk of 1 in 10,000,000 was calculated assuming a casualty number of 1000 persons out of 1,000,000 exposed people and an annual risk of 1 in 10,000 of failure of the Delta works. This number might be outdated, since we know that the number of people at risk is likely to be significantly larger than 1 million, for instance for the dike ring area of Central Holland. Moreover, the number of casualties is more likely to be in the order of 10,000 to 100,000 and the chance of flooding of once in 10,000 years is uncertain. Other reports, like the recent report on external risks from [RIVM \(2003a\)](#), however, also list the flood risk as 1 in 10,000,000 per year. The question now arises how can there be such major discrepancies in the estimated risks. It would be a serious matter if this risk is indeed much higher then generally thought. In particular because the maximum level of any risk in The Netherlands is set, by law, at a minimum of 1 in 1,000,000 per year ([Vrijling et al., 1998](#)). At least, this value is being reported as desirable as a minimum for so-called external safety by the Ministry of Spatial Planning, Housing and the Environment (VROM) in their policy documents, for example in the National Environmental Policy Plan 4 (NMP4, [VROM, 2001](#)).

Table 4 lists the number of people and the surface area exposed to different risks at different levels of chance. It becomes clear that if we assume a risk of a fatality number of approximately 50,000 people due to a dike breach and a risk of less than 1 in 1 million per year and an area which is under this risk amounting to between 1000 to 10,000 km², flooding is a much more severe threat than any of the other environmental risks listed in Table 4. Also, if the same standard of a risk of 1 in 1 million per year had been applied to the locating of new houses, not a single house should have been built in the polders situated well below sea-level. This comparison with other risks illustrates the need for

Table 4. Geographically determined risks in The Netherlands. VR-duty companies are companies that have to report their safety measures every 5 years due to the nature of their activities. (Source: RIVM, 2003b)

Source of risk	Local risk (per year)			
	>1 in 100,000	>1 in 1 million	>1 in 10 million	>1 in 100 million
Number of exposed people				
VR-duty companies	47	800	22,000	149,000
LPG-stations	910	29,000	370,000	790,000
Railway yards	–	3,000	40,000	168,000
Airports	790	19,000	112,000	.
Surface area (km ²)				
VR-duty companies	26	83	212	489
LPG-stations	8	47	208	415
Railway yards	–	3	17	62
Airports	5	30	142	.
Railroad transport	–	9	170	705
Pipelines	.	460	.	.
Transport by road	–	33	630	1,610

reconsideration of the safety levels and an adjustment of the safety regime with regard to floods. A change in weather parameters due to climate change is an additional challenge.

5. THE IMPACT OF CLIMATE CHANGE

From the scientific literature on climate change it becomes clear that the climate, and in particular global average temperature, has changed considerable in the last century, compared to the last 1000 years. Global surface temperatures have increased by 0.6 degrees Centigrade on average. The Intergovernmental Panel on Climate Change (IPCC) concludes that most of this warming is likely to be due to the increase of greenhouse gasses in the atmosphere (IPCC, 2001). For the future in the near-term, say in 30 to 100 years, these greenhouse gasses are expected to lead to climate change. Only the rate of change depends on our success in reducing the emissions. Climate change is likely to affect economic activities, food production, ecological stability and infrastructure.

For the long-term, the impacts are potentially much more far reaching. Abrupt events, although unlikely in the short term, could be triggered by gradual warming and include a reduced strength of the thermohaline circulation (Stocker and Schmittner, 1997) and in particular of the Gulf Stream, which today brings warm and moist air to Europe. Another risk comprises of the positive feedback on the climate when due to warming greenhouse gasses such as methane (CH₄) are suddenly emitted from permafrost soils in sub-arctic regions or from deep-sea sediments. This has occurred in the past and would imply more rapid warming than the warming due to human greenhouse gas emissions alone (Renssen et al., 2004).

Even in the absence of abrupt climate change such as those described above, society will have to cope with a significant set of impacts due to climate change. IPCC (2001) has projected that global average temperatures are expected to increase by 1.4 to 5.8 degrees Centigrade up to 2100, depending on economic development and greenhouse gas emission trajectories. A probabilistic estimate by Wigley and Raper (2001) based on a range of global circulation model results indicates that global average temperatures are most likely to increase in the range of 1.7 to 4.9 degrees Centigrade up to 2100 (90% chance). In Europe the average amount of annual precipitation is expected to increase, in particular in the north and in particular in winter. The southern part and around the Mediterranean is likely to become drier, in particular in summer (Parry, 2000).

Projections of climate change for The Netherlands have been developed by the Dutch Meteorological Office on the basis of a further elaboration of the latest IPCC report (Verbeek, 2003). These are listed in Table 5. Sea-level along the Dutch coast, including land subsidence, is estimated to have risen by 20 to 110 centimetres by 2100. Changes in precipitation are expected to lead to increases in the extreme discharges of the rivers Rhine and Meuse. The discharge of the river Rhine with a return period of once in 1250 years is expected to increase from 16,000 to 18,000 m³ per second (RIZA, 2003). For the river Meuse this amount could increase from 3800 to 4600 m³ per second (Goudriaan et al., 2003).

Changes in storm conditions are much more difficult to predict. The parameters of a storm surge that are important for the strength and height of the flood defence are mostly determined by the direction and strength of the storm, which can increase the water level of the North Sea by 2 to 4 metres. If the maximum wind speed on the North Sea would change due to climate change the maximum water level could also increase. If, however, due to climate change the dominant direction of storms would change (for example from northwest to west), the maximum storm surge level could decrease. The record shows that the number of storms, defined as the past 700 events with peak wind speeds in at least 7 out of 13 locations, has gradually reduced over the past 41 years (Verbeek, 2003). The research by Van den

Table 5. Projected climate change for The Netherlands. The sea-level change estimates include subsidence of the land. (Source: Verbeek, 2003)

Parameter		Estimate		
		Low	Central	High
Temperature	Annual average	+1 °C	+2 °C	+4–6 °C
	Summer	+1 %	+2 %	+4 %
	Winter	+6 %	+12 %	+25 %
Precipitation	Max. 10-day sum	+10 %	+20 %	+40 %
	Recurrence interval	47	25	9
	> 140 mm (currently 100 years)			
Sea-level		+20 cm	+60 cm	+110 cm

Brink et al. (2003) using fairly simple models has shown that storms are potentially sensitive to climate change. Additional research with more sophisticated models is currently underway. For the future it is highly recommended to have more insight in the possible changes of storm intensities and storm track patterns. Small changes in the storm climate on the North Sea can have large impacts, both positive and negative, on the safety level of the North Sea Coastal area.

6. INVEST IN FLOOD DEFENCES, OR ADJUST SAFETY LEVELS?

The Committee on Water Management for the Twenty-first Century, in particular taking into account climate change, has estimated the costs of the adjustment of the water systems in The Netherlands when current levels of safety have to be maintained. These costs would amount to approximately 3 billion Euros for the next 10 years and to 10 billion Euros for the coming 50 years (WB21 report, Tielrooy, 2000). These estimates are likely to be too low. First of all, the more severe wave conditions as observed on the North Sea have not been taken into consideration. Secondly, the potential damages due to flooding and the related motives for certain safety levels and hydraulic standards have not been taken into account. In fact, the WB21 report mainly dealt with the river systems. A similar effort is still to be carried out for the North Sea Coast. An analysis of all aspects that have been described above could lead to an estimate of required investments that is higher than the numbers reported earlier by the WB21 report. Not only the costs of improving the flood defence should be considered, but also the safety level itself. It would be economically wise to have higher safety levels for highly populated and capital intensive areas than for other areas. A differentiation between the different dike ring areas (Figure II) could be refined and adjusted to the values that are present.

The Dutch policy with regard to the safety levels and the protection against floods needs to be reconsidered. More than before, the potential impact of a flood needs to be the starting point for decisions. Reduction of the risk of loss of human lives and property has to be the central issue. A targeted approach to reinforce the flood defence system seems logic. However, the traditional approach should be reconsidered also. A further differentiation in safety levels for the various dike ring areas is likely to be economically attractive and more cost-effective than an overall increase and/or maintenance of safety levels. To expand the possibilities for differentiation the larger dike ring areas could be split up into smaller compartments. The potential losses for each of these compartments should then determine the safety level of each individual compartment. A cost-benefit analysis would help to determine the appropriate investments. By setting new safety levels, decisions on spatial planning, both by citizens and lower governments could be influenced. There could initially be resistance from citizens when in certain areas safety levels would be reduced, similar to current resistance against implementing emergency retention areas in polders along the rivers in the province of Gelderland. The Dutch constitution states in Article 21 that the government has a duty of care with

respect to the habitability of the country and protection and improvement of the environment. Moreover, current safety levels are set by law. Therefore, it appears that some form of (onetime) compensation has to be put in place once safety levels are adjusted. Of course, in the end the levels of protection to be implemented are a matter of (informed) political choice. The introduction of new cost-sharing and insurance arrangements may not only lead to a better absorption of losses, but also to more cost-effective solutions, for instance by promoting risk reduction. Particularly interesting is to see which parts of the risk will be taken up by the government and which parts by the private sector (Bouwer and Vellinga, 2002).

7. CONCLUSIONS

Recent tragic accidents in the Netherlands have received much attention from the public, media and politics. In Volendam on New Years Day 2001, 13 young people died in a café fire. The explosion of a fireworks factory in Enschede on May 13, 2002 left 21 people dead. Both events have lead to countrywide discussions and a plea for more strict inspections and governmental safety standards. However, with regard to floods and presently existing risk levels it can be concluded that a threat involving a potentially much larger number of casualties is lingering. At the same time there is no thorough public debate on the risk of flooding.

It is argued in this paper that the risk of flooding in the most heavily populated dike ring areas, which are also the most low-lying areas of The Netherlands, is too large at present. In a more diverse and partitioned arrangement of dike ring areas a package of measures can be put together. These measures could consist of dike reinforcement and heightening, but emergency plans and escape routes should play a role as well. The idea that the land has to be protected at all costs could also become an issue for debate and safety levels in some areas could be lowered.

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Epilogue: The main findings of our research, dating back to 2003, have since been confirmed by a number of new studies. In late 2004, a major independent assessment of flood safety in The Netherlands showed the relative high risk from flooding, compared to other external risks (MNP, 2004). The interim report of the above-mentioned project into flood risks (*Veiligheid Nederland in Kaart*) showed that flooding probabilities are likely to be higher than the legal standards (Floris, 2005). A second verification round of dike safety indicates that some 24% of the total length of the flood defence systems are not up to standard, and that for another 32% still no judgment can be made (DWW, 2006). In response to these new publications,

and the current lack of commitment by the central government to make the necessary financial provisions for upgrading the flood defences, the Advisory Committee on Water concluded in October 2006 that the government does not succeed in meeting the legal safety standards, and that the country is insufficiently prepared for a large flooding disaster (ACW, 2006). With these notions, the conclusions presented in Section 7 of this paper remain as relevant today.

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CHAPTER 25

PLANNING FOR RIVER INDUCED FLOODS IN URBAN AREAS

Experiences and key issues for Sweden

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Abstract: Problems in urban areas due to flooding are minor in Sweden from an international perspective. However, some events during the last decade have caused considerable damage which has drawn national attention to flooding. As a consequence, flooding has been placed on the political agenda, leading to a number of inquiries into flood phenomena from various stakeholders and committee statements from different levels of government. This paper aims to review some major flooding issues for Sweden, ranging from the role of the hydropower and insurance industries in flood mitigation to the urban planning process

Urban areas bare the brunt of the major consequences of floods, so planning and risk management in cities and towns greatly influence flood risk. An important part of the flood risk mitigation strategy in Sweden is the creation of comprehensive flood risk maps for many Swedish catchments. The low resolution of these maps, however, limits their use in city planning. Here, the planning process is summarized and critically discussed with regard to flood risk

Most of the major rivers in Sweden are heavily regulated for hydropower production. Regulation has had a great influence on flood risk by reducing natural high peak flows in spring and sometimes enhancing the risks during summer and autumn. Thus regulation strategies are reviewed and questioned

The low occurrence of natural disasters in Sweden has led to generous insurance coverage for flooding. An increase in the number of floods in Sweden and major events elsewhere in Europe seem likely to change that with the insurance companies putting pressure on the municipalities to improve their planning and risk management. Thus the role of insurance companies for flood risk planning is discussed

Keywords: urban planning, hydropower regulation, insurance, flood risks, Sweden

1. INTRODUCTION

1.1. Background

The population density and level of investment in urban areas coupled with heightened flood risk means that towns bare the brunt of flood damage costs. Poignant television images of widespread flooding in Europe over recent years have caused a surge of interest in urban flood risk management. Sweden too has suffered river induced flooding - albeit at a smaller scale. Fairly serious flooding occurred in Kristianstad in 2002 and Arvika in 2000 (Svensson et al., 2002), and topically there has been widespread flooding over parts of south Sweden this past summer of 2004. Indeed, some towns that were inundated in 2002 were unprepared for the latest floods and there has been much discussion in the Swedish media.

It is well known that urban areas are more susceptible to inundation than adjacent rural areas due to the high proportion of impervious surfaces (e.g., Maidment, 1993); however, this imperviousness is more important for locally produced flash floods than river induced floods. The causes of urban flooding are many, ranging from poor construction and under sizing of the drainage network to operational problems and system overloading. Here we concentrate on the latter with respect to fluvial floods as opposed to storm- or wastewater management. These so-called *act-of-God* floods can be catastrophic and, obviously, reflect the overall physical conditions within the catchment. As urban areas are often located in lowlands, river mouths and flood plains, they are particularly vulnerable to outside phenomena such as extreme rainfall throughout the catchment, dam-break and downstream river obstructions.

In Sweden, local government is responsible for flood protection in urban areas. Municipalities have a four-tiered planning system with varying legal requirements and support (section 2). Comprehensive plans have the widest spatial and temporal coverage; they signal intention and are not legally binding. Individual building permits lie at the other end of the spectrum, these relate to specific structures and detail the exact regulations that must be followed by developers. Under Swedish law, inadequate attention to flood risk when issuing permits may leave municipalities open to legal action from property owners and insurers upon flood damage (see section 2.3). While there has been some notable work to develop urban flood damage assessment tools internationally (e.g., the Norwegian/German RISURSIM project; Milina et al., 2003), Swedish municipalities often rely on *a priori* knowledge. The rarity of large floods has meant that many municipalities either do not include flooding in their plans or lack the ability to assess flood risk.

Municipalities must answer to the public expectations, insurers and other urban stakeholders, such as property developers, when planning for floods. Effective water management must weigh up flood risk against social tolerance of flooding which is expressed hydrologically in terms of an acceptable event return period or recurrence interval. At its simplest, low end flooding is related to everyday storm-

and wastewater management. At the most complex, planning for catastrophic floods demands some coupling between the management of rural and urban hydrological systems. In general, the greater the risk of flood damage, the lower the tolerance. Thus inner city areas with the highest level of investment and sensitivity have the lowest tolerance.

Concern for flooding has been translated into European Union policy. For instance, the European Committee for Standardization in 1996 recommended that urban drainage systems should be built or rehabilitated to withstand floods with recurrence intervals of between 10 to 50 years depending on the type of urban development and the infrastructure served (European Standard EN 752 External Drain and Sewer Systems).

The ability of Swedish municipalities to set their own level of tolerance has largely been superseded by the European Standard 752. None-the-less, municipalities have freedom over how they will implement the requirements. The standard differs according to land use and there are two sets of hydraulic performance criteria - for storm events (EN 752-2) and inundation (EN 752-4) caused for instance by rivers overflowing. This point is important as it signals a departure from traditional urban drainage design using the design-storm concept towards a more flood-based design concept. Milinš (2000) for instance, gives an example for Trondheim, Norway, where a combination of adverse conditions ranging from high tides to frozen soil caused a 15-year rainstorm to induce a 50-year flood.

Planning based on flood frequency rather than the design-storm may look good on paper, but how should municipalities arrive at the appropriate level of protection when catastrophic events may depend on hydrological conditions outside the urban area. While Swedish municipalities are responsible for local water management and, with a few exceptions, tend to use localized tools for planning, they are affected by decisions made by other catchment stakeholders particularly the hydropower industry which regulates the flows of most major river systems in Sweden. Dam safety is a pertinent question, and experiences in Norway (Midttømme, 2002) and Sweden (Bergström, 2001) have shown how vulnerable towns downstream of reservoirs can be. Effective planning and management at the catchment level can alleviate the problems incurred in urban areas. Indeed, integrated water management for river basins is at the heart of the new European Union Water Framework Directives, but how this will be implemented is not clear in Sweden at the national level, let alone at the local government level.

Insurance companies in Sweden have hitherto provided generous cover for flood damage. Costs to insurers in a specific area are driven by development type and intensity, as well as the frequency and magnitude of flood events. Controversy over climate change (see IPCC, 2001) has intensified the debate over who has responsibility for property damage. That is, are municipalities culpable if they allow development in areas which may be subject to increased future flood risk?

While climate change may affect flood hazard in Sweden (e.g. [Arnell, 1999](#); [Persson, 2003](#)), the issue is outside the scope of this paper and will not be addressed.

1.2. Objectives and Overview

The introduction has pointed to a complex situation in most Swedish municipalities with regard to flood risk assessment and planning. The objective of this paper is to elucidate this situation and critically analyze it with regard to a few main themes. Thus, this paper will:

- review the urban planning process with respect to flood risks
- illustrate flood mitigation in Sweden by discussing selected cases
- assess the role of the hydropower industry with respect to river regulation and dam safety
- review the way in which insurers influence municipal flood risk management

2. FLOODING AND THE PLANNING PROCESS

In Sweden, municipalities are responsible for land and water planning within their borders. There is a hierarchy in the planning process ([Figure 1](#)) whereby: a comprehensive plan covers the entire area of the municipality; evolving from this plan are area regulations for specified zones; finally, detailed development plans are most often in force for central and sometimes suburban areas. Furthermore, practically all urban development is subject to individual building permits. Although municipalities are autonomous with responsibility for their own planning, their

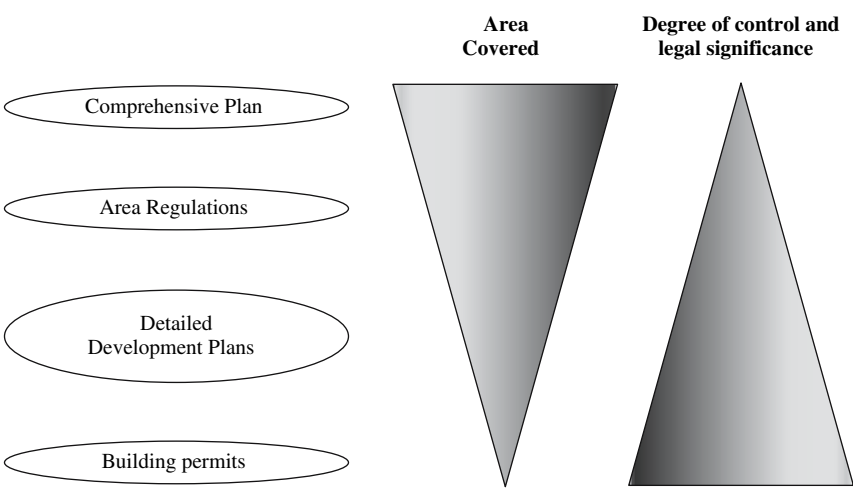


Figure 1. Schematic of the planning hierarchy in Sweden, indicating the relative area covered and degree of regulation at each level

work is supervised regionally by the District Administrative Board (*Länstyrelse*) and nationally by the National Board of Housing, Building and Planning (*Boverket*) (Ch 1, 8th § of the Planning and Building Act, SFS 1987:10 (*SFS = Svensk FörfattningsSamling, the Swedish legal corpus*)).

2.1. Comprehensive Plans

Comprehensive planning is not legally binding and the municipality is not obligated to adhere to these plans. They are used primarily as a guideline and support for the municipality and its committees for decision making on land and water usage. However legislation still demands that:

The comprehensive plan shall account for (...) the environmental and risk factors that need consideration when decisions are made on the use of land and water areas (from Ch 4, 1st §, SFS 1987:10).

A *Boverket* inventory of comprehensive plans for different municipalities has shown that most make no mention of flood risks ([Lundquist, 2001](#)). While it is true that the magnitude may differ greatly, most municipalities do, in fact, face some flood risk. Furthermore, of those plans that do cover flood risks, there are large differences in approaches taken. Some municipalities have written only a sentence or two, while others (precious few) have made serious attempts to identify risk by studying several possible scenarios.

In some cases comprehensive plans function as information resource material for potential residents and new businesses; a prospectus which highlights the advantages and disadvantages of the municipality. This double use of the plan can lead to a certain conflict of interests, particularly if information takes precedence over planning. For instance, there may be a tendency to neglect risks in the text so as not to discourage investment within the municipality. While understandable in municipalities in need of more residents and capital, this use of comprehensive plans does not fulfill their main purpose, that is, to facilitate detailed development planning and aid in the granting/refusing of building permits.

2.2. Area Regulations and Detailed Development Plans

Area regulations and detailed development plans are legally binding, thus any mistakes within them can prove expensive for the municipality. Area regulations typically dictate what kind of development is allowed in an area, for instance whether it is a residential or industrial zone. The detailed development plans go further by putting strict limitations on the size and shape of buildings to be constructed in an area. Most urban areas are at least subject to area regulations, and the denser the population the higher the proportion of land covered by these plans.

When it comes to flood risk, the municipalities with greatest awareness have zones where either all new construction is prohibited or where special restrictions

apply, say no basements and a minimum elevation for the ground floor. Regrettably, most of these zones have been identified after some flood event without establishing how extreme that event was or the likelihood that the area will be exposed to an even greater flood. For example, the Ovanåker and Falu municipalities in central Sweden used the water levels from a flood in 1985 to determine the threshold for further residential settlement. Likewise, Torsby Municipality takes a flood in 1987 as the archetype for flood risk management (Lundquist, 2001). Generally, basing flood risk management on an event of unknown probability is a “shot-in-the-dark”.

The Swedish Meteorological and Hydrological Institute (SMHI) has created overview flood maps for most Swedish rivers under a commission from the Swedish Rescue Services Agency (e.g. SRV, 2002). For each river basin, the areas flooded by the 100-year flood are shown along with the areas that would be flooded by a design-flood for risk class I dams (approximately a 10 000-year flood, see section 4.4 below). These maps constitute an important first step towards standardized flood risk management for municipalities. However, they have low resolution which limits their usefulness for detailed planning. Indeed, they were never intended to act as sole data for detailed development planning or individual building permits. Municipalities are supposed to identify which areas need to be mapped with a higher level of detail. Nevertheless, complaints regarding the resolution are common from municipalities (e.g., Friström 2003). To facilitate a high standard, one option could be the production of high resolution flood maps by a government agency on a national scale. This would be extremely expensive today, but imminent improvement in resolution in the national topographical map (Personal comment, Petter Pilesjö, 2003) will cut this cost considerably.

The question remains as to whether these levels, that is the 100-year and $\sim 10\,000$ -year floods, are appropriate for municipal flood risk management. If a building within a 100-year flood zone has an estimated lifespan of 50 years, the risk of flooding at least once during that time is 40% or higher. This may be a higher risk than many property owners would be willing to take, if they were aware of it. On the other hand, the 10 000-year flood is too extreme an event to use, at least when deciding on the location of residential buildings. Thus flood risk must be weighed against the benefit lost by not developing an area, so the acceptable flood hazard should depend on the kind of development planned.

2.3. Building Permits

At the end of the regulative planning spectrum lie individual building permits. These are legally binding and regulate in detail what is to be built under individual development applications. The Swedish Supreme Court has found that municipalities can be held accountable for damage due to unsuitable location if they grant a building permit:

When planning and granting building permits, the building committee shall take special care to consider the reported circumstances. Damage liability for fault or neglect by the building committee will arise

mainly when the municipality, in light of special local knowledge or special resources, has a better ability than the constructor to understand the risk of damage and judge what measures should be implemented (Translated from [Didon, 1993](#)).

This paragraph enables the owners of a flood damaged property, or their insurer, to demand compensation from the municipality. Claims that the municipality has better resources than the individual to judge flood risk are foreseeable. Hence granting building permits in a flood prone area is inadvisable.

Despite the critical tone in this section, it must be mentioned that during the summer floods of 2000 in central Sweden, no structures with building permits dated after 1990 were damaged ([Lundquist, 2001](#)). This can, on the other hand, be partly explained by the fact that construction was extremely low in Sweden during the nineties. An average of only 8907 single-family houses were built annually during the period 1991–2000, compared to 29543 annually during the previous three decades, that is a 70% reduction in construction ([SCB, 2003](#)).

3. WATER FRAMEWORK DIRECTIVE

The Water Framework Directive (WFD, 2000) was adopted by the European Union (EU) in December 2000. The main objective of the WFD is to keep, protect, and where necessary, restore, the natural integrity of aquatic ecosystems. The directive covers both surface water, including coastal zones, and groundwater. The main focus of the WFD is water quality, but it also fully recognizes the total dependence of ecological status on issues related to quantity. A major feature of the WFD is the requirement that member states implement water administration organized according to river basin boundaries. Preparations for the adoption of WFD have been made over many years, but the first formal deadline was December 2003 when the legal basis should have been in place in the member states.

The first article (1e) of the WFD states that one of the purposes of the new directive is to reduce the impact of floods. However, the directive does not explicitly say how this should be achieved. Furthermore, article 3.3.a of the directive allows for exemptions to the ecological requirements in cases where such requirements would severely affect the level of flood protection, this can be seen in the strategic document, ([WFD, 2001](#)). On a more general level, it is clear that the strong emphasis on integrated river basin management provides the opportunity for truly coordinated flood prevention and mitigation.

In Sweden the preparations for the implementation of the WFD have been ongoing for several years. The proposition from the government regarding new legislation was approved in March 2004 and has been incorporated into law as an ordinance ([Swedish Parliament, 2004](#)).

The situation in Sweden with respect to flood protection strategy and management leaves room for improvement. It should be clear from this paper that, for example, the planning process and instruments in urban areas do not promote optimal development from a flood protection point of view. The adoption of the WFD will enable more emphasis to be put on water related issues. It has even been

suggested (SOU, 2002) that, when necessary, water issues may take precedence over municipal planning for other purposes. Furthermore, with its focus on the river basin, the WFD could be used to encourage authorities and organizations to take a holistic approach to flood protection with cooperation across present administrative (municipality and county) borders in Sweden.

It is not yet clear how water management in general and flood protection in particular will be affected by the implementation of WFD in Sweden. But, as described above, it has the potential to change flood protection strategies and management for the better.

4. FLOOD MITIGATION EXAMPLES

Hydrologically, social tolerance is expressed in terms of the x-year recurrence interval flood. Tolerance differs according to the severity (cost) of the flood consequences against the cost of flood protection and is determined using some form of cost benefit analysis. Figure 2 demonstrates the principles. The greater the recurrence interval, the greater the overall damage and the greater the cost of flood protection. While the cost of a severe flood may be high, the average cost (i.e., cost of system failure/recurrence interval) may be less on an annual basis compared to more frequent flooding with lesser consequences. Counting the costs of flood

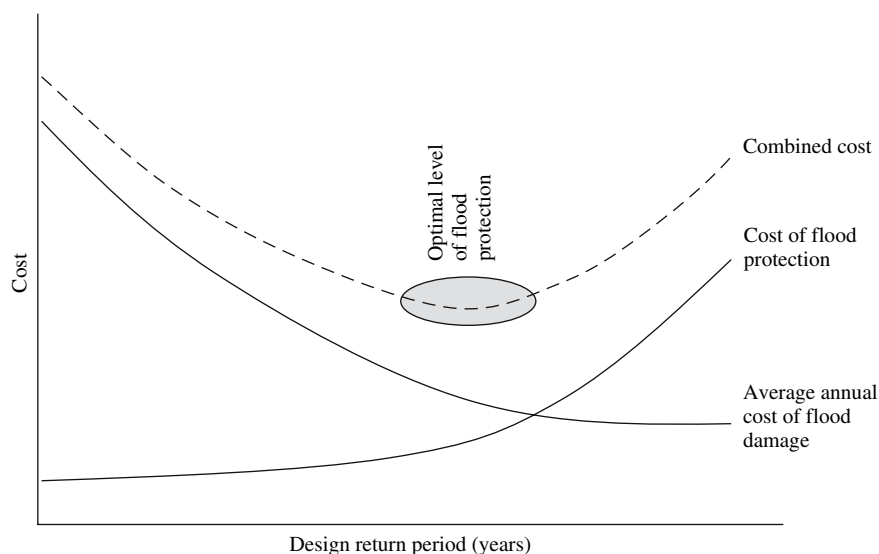


Figure 2. Cost comparison for flood protection versus flood damage averaged over time. The optimal level of protection refers to the point where the sum of protection and damage are minimized (Modified after Milina et al., 2003)

damage is problematic as floods affect quality of life as well as the cost of repair. Non-monetary costs can range from disruption of traffic and minor water damage to destruction of property and loss of life or limb.

Ironically, a town with successful flood protection measures may fall victim to that success as land values rise; a typical scenario is pressure for development of river- or lake-side real estate. This proved the case for Kristianstad, a riverbank city in south Sweden which is particularly susceptible to flooding as some of the oldest parts of town lie below the channel-full level. Flood walls and pumps have been in place for decades and had effectively eliminated small scale flooding leaving the town unprepared for extreme events. During a period of persistent rainfall in spring 2002, severe damage was only avoided by round-the-clock sandbagging. The near disaster has acted as a catalyst for action and the municipality has implemented a major catchment-wide modeling scheme to better plan for floods in the urban area (See [Wettemark et al., 2003](#)).

Similarly, flood protection is at the centre of preliminary plans for a high-cost housing estate in Arvika. Arvika lies on the shores of Kyrkviken Bay which is part of Lake Glafs fjorden. The bay is almost circular and is connected to the main lake by a narrow strait as can be seen in Figure 3. Note that this figure is modified after one of the SMHI overview flood maps discussed above and shows both the town and the flood zones for a 100-year event.

Intense autumn rains in 2000 caused the water level of Lake Glafs fjorden and Kyrkviken Bay to rise 3.03 meters above the mean level ([Svensson et al., 2002](#)). This led to severe flooding in the town, but emergency action carried out for several weeks by rescue workers and other municipal personnel, military personnel and volunteers kept vital services operating and protected important buildings. As a consequence of this flood, barriers have been planned in the strait and on lowland areas on both sides of the strait; the positions are indicated in Figure 3. The barriers will have integrated pumps to enable a difference in water level between the lake proper and the bay of up to 2.5 meters. The proposed barriers will have total construction cost of 31.7 million SEK plus 0.2 million SEK annually for maintenance ([Botström & Engström, 2002](#)). For comparison, the documented costs for Arvika municipality alone was 84 million SEK following the 2000 event, excluding damage to national roads, railways, private property, commerce and industry (*ibid*).

Even though these barriers are probably a wise decision, the prospect of future flood protection has sparked plans within the municipality to develop lakeside areas around the town in a way that would never have previously been considered. This means that the economic losses from floods could be substantially increased. While lowering flood frequency, there are limits to the reliability of the structures and pumps. Thus, some probability of flood will remain. Seeing risk as a function of probability and consequence, means that the initial risk reduction (reduced frequency) provided by the barrier could diminish or even disappear altogether with post-barrier development (increased consequence).

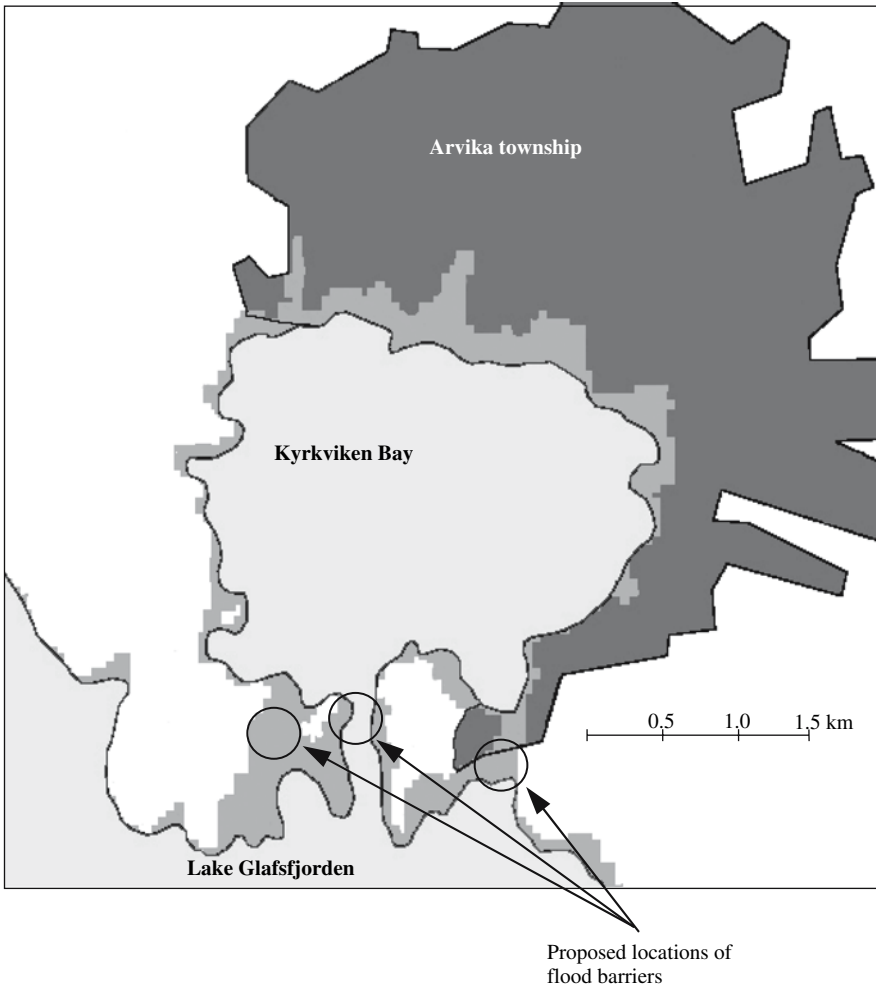


Figure 3. Overview of the flooding situation at Arvika showing the town (dark grey), lake and bay (light grey) and the SMHI simulated flood extent (medium grey) for the 100-year flood. The locations of the proposed flood barriers are indicated. (after SRV, 2002 ; [Botström & Engström, 2003](#))

5. THE ROLE OF HYDROPOWER

All major Swedish dam-constructions are managed by hydro-power companies and the motive behind their operating strategy is first and foremost to optimize power production seasonally. Flow is regulated in most of Sweden's major rivers by a complex system of dams and reservoirs. An illustrative example is the River Ångermanälven and its tributaries. In this system there are 60 reservoirs, 45 power stations and one bypass ([Bergström, 1999](#)). Figure 4 gives a comparison

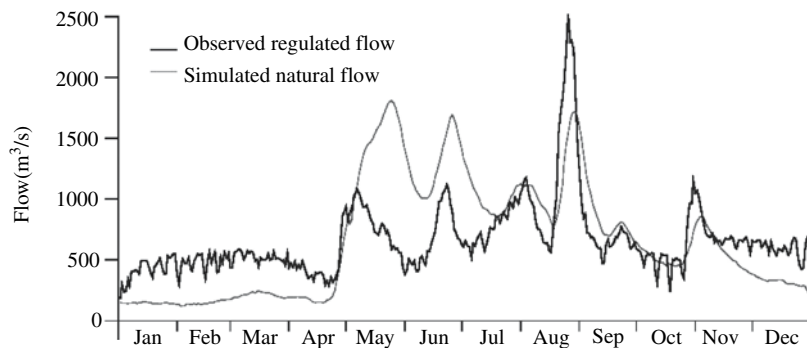


Figure 4. Observed regulated flow (Bold) against simulated natural flow (Fine) for 1998 at Sollefteå on the River Ångermanälven (with permission after [Bergström, 1999](#))

for this river between the actual, regulated, flow recorded at Sollefteå during 1998 and an SMHI simulation of unregulated flow. Thus, not only are flow patterns of Swedish rivers changed, but regulation also substantially alters the way they flood.

There are important differences in pre- and post regulation flow patterns of regulated rivers. Large spring floods due to snowmelt are either removed or reduced as reservoirs – which have been depleted for winter power production – are refilled. This aspect is illustrated in Figure 4 by the peaks in May and June. It is worth pointing out that winter is a time of low-flow where water release is not matched by inflow. Floods due to summer storms and autumn rains can also often be reduced by prudent regulation of the reservoir system, provided the reservoirs are not already filled to the design limit.

However, these same floods can also be intensified by regulation as can be seen for August and November. With the dam in place and the water level at the maximum design level (i.e., no further retention of water is possible), all incoming water must be released in order to avoid (or minimize) the risk of dam break. In a natural river and lake network, lake water levels can often increase beyond bank-full, that is, the lake can retain some of river discharge by inundating the surrounding area rather than downstream flooding. Furthermore, natural lakes usually have low water levels following summer, while dam-regulated power-production reservoirs are kept at a higher level for production the following winter. In a dam-regulated reservoir at the maximum design level, the ability to retain inflow is eliminated so that the outflow can become considerably greater than would occur in an unregulated river. According to Figure 4, the autumn flood at the end of August would have been much less severe had the river not been regulated. The effect is more subtle for the November event, but as the reservoirs are usually full for winter power production at this time of year, heavy rainfall could have had disastrous consequences.

5.1. Element of Surprise

Another important difference between regulated and unregulated rivers is the element of surprise surrounding floods. As flow-regulation can cope with many would-be flood situations, minor inundation which used to be fairly regular may cease. That is, the floods that do occur tend to be at the more extreme end of the spectrum. Sadly, regulation can lead to a false sense of security for people living near rivers and on flood plains as flood awareness is lowered over time. As with urban flood protection mentioned above, the very safeguards in place to reduce flood risk may leave people vulnerable to flooding, especially if development has been allowed at inappropriate locations.

5.2. Regulate More Wisely?

Besides the goal to optimize the flow to the turbines over long time periods, all dams must operate within a frame set by an individual ruling from the water courts. This ruling limits aspects like the water-level in the reservoir and changes in outflow. The question arises as to whether the regulations can be managed to alleviate the risk of flooding. The answer is yes, but only to a certain extent as was shown by [Bergström \(2001\)](#) in the case study detailed below.

The same wet weather that affected Arvika caused the regulated rivers of central Sweden to experience high flows during summer and autumn 2000. These flows were thoroughly analyzed by SMHI on behalf of the Swedish power grid owners, Svenska Kraftnät (see the appendices of [Losjö, 2001](#); [Magnusson & Milt, 2001](#)). One particular scenario ([Bergström, 2001](#)) compared regulation orientated towards flood reduction to the optimized power production approach which all the major dams in Sweden have been designed and constructed for. The results for the Torpshammar Power Station are outlined here. For the 2000 inflows, the peak bypass flow (i.e. flow which bypasses the turbines) from the dam could have been reduced by approximately 25%, had the reservoir been only half-full at the beginning of the precipitation event rather than nearly full as it was.

The potential flood reduction must be weighed against the consequent financial risk of perhaps not being able to fill the reservoir before winter sets in when inflows are low and power demand is high. The cost/benefit analysis is complicated by the fact that the costs and benefits belong to different stakeholders. The costs (i.e., the financial risk of only partially full reservoirs) belong to the power producers, while the benefits (i.e., reduced flood risk) belong to private and commercial interests downstream from the dam. Economically dam owners are liable for any third party damage following a dam failure, but the immediate risk is certainly not limited to monetary aspects. Therefore communication is essential among the stakeholders, preferably with the authorities playing a leading facilitative role. This role may become clearer following the implementation of the Water Framework Directive, discussed in section 2.4 above.

[Bergström \(ibid\)](#) points out that to achieve the mentioned peak flow reduction, the reservoir would have been almost at its full capacity by the end of the event. Thus,

had the event lasted a little longer, or been a little more intense, the reduction would have diminished or even disappeared altogether. Recall that this simulation assumed half-full initial conditions. The simulation begs the question as to whether flood orientated management is viable, particularly as the 2000 event at Torpshammar was rare. Indeed, the flow was the greatest measured at this location since regular measurements began in 1915.

Work is currently being undertaken at Lund University and the electricity supplier Sydkraft to forecast seasonal weather several months in advance for hydropower production planning (Personal Comment Cintia Bertacchi Uyd, 2003). This research could also prove useful for flood management. For instance, winter 2002/3 followed a drought autumn and was cold and dry in agreement with a strongly negative phase of the North Atlantic Oscillation (NAO; see e.g. Hurrell et al., 2003; Marshall et al., 2001). Thus, there were low spring levels in all the major hydropower reservoirs leading to exceptionally high electricity prices that persisted throughout 2003 (Nordpool, 2003). If winter snowfall is predicted to be low, it does not make economic sense to release water in autumn beyond that needed for power production, particularly as the flood risk would then be slight for both autumn and spring. If, on the other hand, a wet autumn is to be followed by a snow rich winter (positive NAO), it makes sense to lower the pre-winter water level to reduce risk of both autumn and spring flooding.

Before any changes are made in the management procedures of any dam, the expected consequences for the entire river basin should be investigated. A local improvement may be outweighed by detrimental effects at other locations. This can result in a very complex analysis for a large basin with several different tributaries. The uncertainty of the effects can never be entirely eliminated, since the inherent spatial and temporal variability of possible precipitation events, and thus flow-patterns, is nearly unlimited.

It must also be kept in mind that any successful alteration in regulation strategy will add to the element of surprise mentioned above. To reiterate, success in this context means lowering the frequency of flooding rather than eliminating risk. Therefore if risk communication is inadequate between the dam managers and the planning office of downstream municipalities, the paradoxical situation may arise that while flood frequency is lowered, flood risk is actually increased due to increased losses when flooding occurs.

5.3. Dam Safety

During a high flow situation, the integrity and safety of the dam takes priority over all other aspects. This is because a major dam break could have catastrophic consequences for all stakeholders (e.g. Midttømme, 2002).

The analysis of the high flows in 2000 by SMHI (Losjå, 2001) also considered reservoir water levels and the outflow in comparison to the maximum design outflow. It was found that the water level in several cases exceeded the maximum allowed level. Despite the fact that water did not flow over the crest of any of the

dams, the outflow in some cases exceeded the maximum bypass flow, thus dam safety would have been compromised if the flow through the turbines had stopped.

Two small dams in minor tributaries of regulated rivers did collapse during 2000, one by the water force alone and the other following a risk management decision to actively undermine the dam using excavators. These small dam breaches had minimal consequences. But even the larger dams reported several problems. Many became hard to reach as the connecting roads were washed away. Inaccessibility can be a risk in itself, for instance by blocking access to heavy equipment such as mobile cranes, which can be needed to open hatches. Minor to intermediate problems were reported from many dam operation centers and power stations (Lofsjö, 2001).

These circumstances could have been deemed acceptable for a truly exceptional flow. But for most of the regulated rivers of central Sweden, the 2000 high flows were not the highest on record. Flow was close to a 100-year event in some cases, less in others. Calculating an exact recurrence interval is difficult for these rivers as they were gradually regulated during the twentieth century with consequent changes in conditions; but the probability of having as high-a-flow, or higher, in the immediate future is far from negligible.

There may therefore be another reason for considering the water level strategy for the reservoirs – namely dam safety. Swedish dams are divided into two risk classes depending on expected dam breach consequences. New dams in the lower risk class (II) must have a bypass capacity of at least the 100-year flood, while new high risk dams (class I) must have a bypass capacity of a worst case scenario, specifically modelled for each river basin – a kind of a Probable Maximum Flood (see also Klintberg *et al.*, 1990). As noted above, the recurrence interval for this flow is approximately 10 000 years. Several existing dams have a considerably lower bypass capacity than their risk class dictates (Lofsjö, 2001). In these cases it may be reasonable to use a more careful approach on water level such as not allowing the reservoir to reach full capacity until the verge of winter, or even later depending on whether rain or snowmelt events are common following the first frosts. This should of course be an individual consideration for each dam, since the flow regimes and capacities vary greatly.

6. THE ROLE OF INSURERS

At present, all the major insurance companies operating in Sweden have the following standard definition for compensatable flood damage in home insurance policies:

(Damage caused by ...) water that follows a storm (intensity >1 mm/min or >50 mm/day), snow-melt or rising water levels in lake or watercourse and enters a building as backflow through sewerage or as surface flow through doors, windows or valves.

These conditions are met in most river induced floods that occur in Sweden, although they exclude some situations, for instance, when the foundations are water damaged without water actually entering the building, or when water enters by

seeping through cracks below ground level. Consequently, major fluvial floods could prove costly to Swedish insurance companies: Indeed, there is anecdotal evidence that insures have sought and received compensation from municipalities in cases where the physical planning has been less than satisfactory in the flooded area. However, concrete information is difficult to get hold of due to the commercially sensitive nature of the cases.

Floods resulting from dam breaches are a special case and home insurance policies give a maximum compensation of 70,000 SEK, which is only a fraction of the costs if a building is seriously damaged. The owner of a dam has, however, absolute liability for the damage following the malfunctions of a dam.

Swedish insurance companies have surprisingly few data on flood risks in specific geographical areas. Or at least these were not readily available to the authors. Generally, flood damage is lumped with other water-related damage such as pipe or valve breaks and leaks from home appliances (dishwashers, washing machines *etc.*). These are of course much more frequent than actual flood damage, but rarely as costly.

The apparent lack of data is surprising because knowing the risk of damage is essential for an insurance company when deciding the optimal insurance rates. The reason for this situation is that costs for flood damage have been low in Sweden compared to losses due to other natural phenomena such as windstorms, and minimal compared to fire losses. Swedish insurance companies apply a package rate for policies which cover both fire and natural hazards, thus they do not specify insurance rates with regard to flood risk. Recent flood events have, however, prompted insurers to revise how future policies should look. A shift towards staggered rates in flood prone areas seems much more likely than refusing new policies as has been the case in some areas in Germany that were flooded in 2002 (Oral presentation, Markus Reinke IOER Dresden at [Svenskt Miljöforum 2003](#); [Swedish Environmental Forum 2003](#)).

Despite the need for flood risk know-how within the insurance business, the risks are practically impossible to calculate to any degree of certainty as long as municipal flood risk management is neither standardized nor reliable. With the present level of knowledge, each individual insurance contract would need a major investigation to fully determine the flood risk involved. This is certainly not cost effective, furthermore it is a cost that nobody is prepared to pay. Consequently, the insurance industry would benefit from and will advocate for better municipal flood risk management.

7. CONCLUSIONS

Based on the discussion presented in the previous sections, the following conclusions regarding key issues for improved management of river induced urban flood risks in Sweden are made:

- **Comprehensive plans.** The municipality-wide comprehensive plans are supposed to point out all the relevant risks as an aid for decisions regarding land use. However, only a handful of these plans mention flood risk to any great extent,

and the majority have no reference to them at all. Thus, the foundation for sound planning is lacking, and in this respect Swedish municipalities largely do not follow present legislation. A further complication has arisen due to the implementation of the EU Water Framework Directive. With the new water authorities in charge of all matters concerning water resources, it is not quite clear who will have the final say in cases where measures for flood damage reduction interfere with the land planning process.

- **Detailed development plans.** Flood risk management often enters the physical planning process at the area regulation or detailed development plan level. Unfortunately, a scientific basis for defining flood risks is usually lacking, that is, if risk is addressed at all. Flood risks are met on an *ad hoc* basis; the plans quantify neither flood frequency nor consequences. Detailed development plans cover only limited areas, and, hence, by not addressing flood risks at the comprehensive plan level many municipalities have fragmented flood risk management.
- **Flood maps.** The overview flood maps produced to date for major Swedish river basins are an important first step towards standardized flood risk management. However, these maps need higher resolution to be truly applicable in the urban planning process. Like the maps currently available, high resolution maps should preferably be produced by a government agency to maintain a national standard. The production cost for such maps would be extremely high today, but ongoing improvements in the resolution of the national topographical map will cut this cost considerably.
- **EU Water Framework Directive.** Integrated flood risk management is difficult in Sweden since water management is fragmented both geographically and organizationally. Even within municipalities, water management is often split between different offices. Another difficulty is that each municipality is the sole body responsible for planning within its borders and calls for wider co-operation have been seen as a threat to this autonomy. Adapting and implementing the new EU Water Framework Directive will hopefully improve this situation through a stronger focus on river basin management.
- **Reservoir management.** Normally Swedish reservoir management is optimized with respect to hydropower production with little heed to downstream flood risks. With present limitations in precipitation prediction, it is difficult to take flood risk into consideration without substantially increasing the economic risks of loss of hydropower production capacity during winter and indeed, the following seasons. Improved long term prediction could facilitate more flood risk conscious management of reservoirs, but it would also increase the element of surprise as flooding will occur eventually, albeit less frequently.
- **Dam safety.** Another, perhaps more immediate reason to oversee reservoir management is the fact that dam safety is not as high as one might expect in Sweden. The high flows of summer 2000 in central Sweden were not terribly extreme with respect to design standards; a couple of rivers experienced approximately 100-year floods, others had floods with considerably lower return periods. Nevertheless, two minor dams gave way and near emergencies were reported

from several major dams. The bypass capacity of many existing Swedish dams is much lower than would be demanded if they were constructed today. As long as this is the case, even more attention must be paid to safety aspects in reservoir management.

- **Insurance as a driving force.** With the exception of the last decade, costs associated with flooding have been low in Sweden with respect to other phenomena, and insurance companies have not shown a great interest. However, the flood situation has worsened dramatically in recent years, and insurers are now changing their policies with regard to flood damage. Moreover, insurers are increasingly likely to seek compensation from negligent parties. Certainly, the changes which have and will come about will put pressure on other stakeholders to act with greater responsibility.

In summary, most of the key issues mentioned above are related to adequate information (or, rather, a lack thereof) regarding flood risks in Sweden. Better access for individuals and organizations to correct and relevant information regarding the consequences of their actions for themselves and for other stakeholders would strengthen sound flood risk management. Following the increased attention paid to flooding over recent years, there are now several ongoing initiatives and processes which will improve the situation. However, considering the high stakes, the implementation of these needs to be accelerated.

This chapter was written in the autumn of 2003 and there has been some development in the field since then. The county administrations of central Sweden have for instance published guidelines for municipal land-use planning with regard to flood risk, which when implemented will have a significant effect on what kind of development is allowed in flood prone areas.

Also the municipalities of Sweden have increased their risk management activities and capacity during the last years, which should enable them to address flood risk better.

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CHAPTER 26

INTERREGIONAL AND TRANSNATIONAL CO-OPERATION IN RIVER BASINS – CHANCES TO IMPROVE FLOOD RISK MANAGEMENT?*

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Abstract: In European river basins many flood management and protection measures are planned. However, the realisation of effective but space consuming measures such as retention areas and dike relocation mostly lags far behind time schedules. The development and set-up of an interregional and transnational basin-wide co-operation structure ('flood management alliance') is substantial to realise catchment oriented flood management. In particular, this co-operation structure must involve spatial planning. The interregional and transnational co-operation structure establishes the framework for the joint accomplishment of instruments for flood risk management which is basin-wide agreed on. One of these instruments comprises financial compensations between downstream and upstream regions which shall improve the acceptance and the realisation of measures which bear disadvantages for the regions where measures are located. Existing and planned basin-wide co-operations in large transnational European river catchments demonstrate reasonable developments towards these goals. However, further efforts have to be made to exploit the chances interregional co-operation offers for improved flood risk management

Keywords: spatial planning, flood management, interregional co-operation, burden sharing, risk management

Abbreviations: AER Assembly of European Regions
ELLA Transnational project ELBE – LABE Flood Management Measure by Transnational Spatial Planning (INTERREG IIIB-project)

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ESDP	European Spatial Development Perspective
EU	European Union
ICPE	International Commission for the Protection of the Elbe/Labe
ICPO	International Commission for the Protecting of the Oder
ICPOAP	International Commission for the Protection of the Odra River against Pollution
ICPR	International Commission for the Protection of the Rhine
IKSO	Internationale Kommission zum Schutz der Oder (=ICPO)
INTERREG	European Community initiative which aims to stimulate interregional co-operation in the EU. It is financed under the European Regional Development Fund (ERDF).
IRMA	INTERREG IIC Rhine Meuse Activities (1998–2001)
MKRO	Ministerkonferenz für Raumordnung
NGO	Non-Government Organisations
NRW	North Rhine – Westphalia
SPONGE	Scientific Programme ON GEnenerating sustainable flood control (INTERREG IIC-project)
UN	United Nations

1. PREFACE

To meet the future demands for sustainability all approaches of spatial and environmental planning can no longer be seen as separated in different spatial units which are not linked to each other. The transboundary impact of natural hazards and the internationalisation of political solutions call for transnational co-operation in planning and regulation. Interregional and transnational co-operation of all different actors involved and on different levels have become more and more substantial. This is politically and scientifically required (see [UN, 2000](#); [EU, 1995](#); [MKRO, 2000](#)). Thus, approaches have to be adapted to reflect current regional and national needs so as to promote voluntary co-operation amongst actors in order to force co-operation where necessary. Furthermore, incentives should be created to raise the willingness to co-operate amongst stakeholders.

The EU Water Framework Directive (WFD) provides a good starting point for catchment wide policy, but it falls short in addressing spatial planning and flood issues. It is important that basin wide co-operation in river basin management and flood prevention has to become common practice, which must be facilitated by EU policy.

This chapter tries to summarise the demand on the different co-operation styles for spatial planning oriented flood management in large river basins. It gives examples of the state of art for the Rhine, Oder and Elbe basins. The focus is laid on flood risk management strategies for entire large river basins.

The scientific basis for this publication are various EU-funded research projects (e.g. INTERREG IRMA SPONGE) and practical implementation projects (e.g. OderRegio, ELLA) that have been worked out by the authors.

2. NEEDS FOR CO-OPERATION

As a transnational framework for interregional co-operation, binding agreements exist at the transnational level between the countries involved regarding water management targets and flood protection along the large European rivers e.g. Rhine, Elbe, Oder or Danube. They are laid down in action plans on flood defence of the transnational river commissions (e.g. for the Rhine: ICPR [1998]). The outreach and impact at regional and local level, as well as local acceptance, is considered inadequate. However, the implementation of the strategic plans is in the responsibility of local and regional authorities. That, it is difficult to meet the goals of the action plans on flood defence in many cases (e.g. ICPR [2001]). A concrete transnational and cross-regional working level must be created to be responsible for the control of land use with regard to regional flood protection considerations and to make economical solutions possible. Such structures dealing with tasks of spatial planning have proved very successful in many cases and responsibilities other than flood management like waste management in interregional frameworks. The urgent tasks in preventive flood management that especially call for excellent co-operation structures are e.g.:

- Working out and agreeing on visions and strategies for transnational river basins, including measures, budgets, timeframes.
- Production and continuous agreement procedure on a catchment area-wide, cross-regional, spatial planning action program for all fields of action in spatial planning to implement the action plans on flood defence.
- Extension of the action plans including concrete regional planning.
- Adaptation of flood-relevant contents of the action plans in the individual regional plans as well as their communication with the municipalities.
- Creation of incentives and increase of acceptance in reclaiming large retention areas and burden sharing agreements.
- Creating a framework for negotiations to address upstream – downstream relations.
- Increase public awareness.
- Monitoring of processes and achievements of regional planning in all preventive flood management efforts.

Different styles of co-operation can be distinguished: vertical (i.e. EU-Nations-Regions-Cities), horizontal (i.e. cross boundary) and inter-disciplinary. Vertical co-operation is ruled by legislation and functions more or less effective. It is not the focus of this article since it is not the major concern of voluntary steps. On the other hand, forced horizontal co-operation is strictly limited by the independence of nations, regions and municipalities in Europe. Therefore, this kind of co-operation is an excellent field to be improved by applying voluntary principles. However, in all cases different actors will have to work together closely on solutions for flood risk management. The so called interdisciplinary co-operation is already well accepted and not subject to far reaching disputes. Even more it is the fundamental for all co-operation initiatives.

3. CONCEPT FOR IMPROVED CO-OPERATION

3.1. Levels of Co-operation

Due to their competence and practical possibilities, the co-operation levels within a catchment area each have specific tasks (see Figure 1):

Within the framework of the EU and with regard to the catchment area-wide water management, transboundary co-operations gain in importance. The national level is important for (international) co-operation, since here, legitimised democratically, perspectives and strategies for the spatial development are defined. The limited number of partners at this level within transnational river basins represents a comparatively favourable condition for agreements between the partners. However, this level does not achieve concrete planning and mostly has no direct influence or control on land use decision.

According to the Assembly of European Regions ‘Declaration on regionalism in Europe’, an European region is defined as “...the territorial body of public law established at the level immediately below that of the State and endowed with political self-government. The region shall be recognised in the national constitution or in legislation which guarantees its autonomy, identity, powers and organisational structures.” (AER, 2001). The regional level is in most European countries a democratically legitimised authority with extensive authority for regional planning. Thereby, it can make direct obligations for spatial use. Although this level is not responsible for concrete land use decisions, distinct possibilities exist to direct the municipalities regarding regional requirements. As a rule, the number of regions in transnational river catchment areas is too large for the creation of a genuine working group in the context of a co-operation structure. A further subdivision into clusters is necessary (see below).

In most European countries the local level is decisive for concrete land use decisions, and partly also for building permits. It is shown that local spatial planning

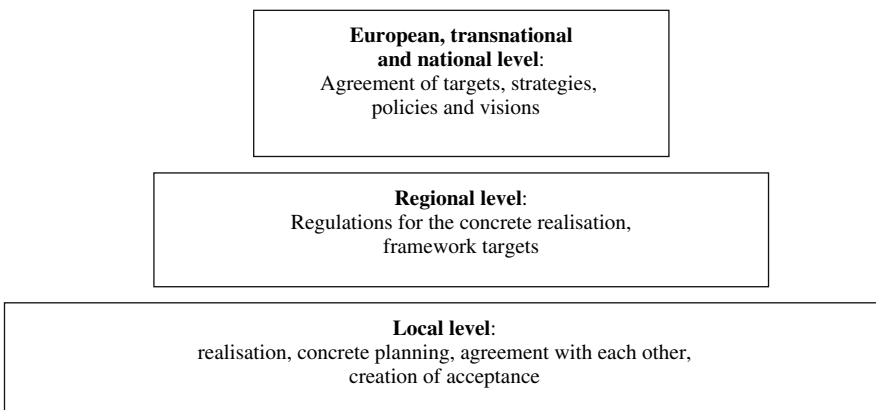


Figure 1. Scheme of levels and competencies of spatial planning

instruments exist and can successfully be used according to the criteria of flood damage prevention if the public and political awareness is sufficient (see e.g. Böhm et al., 2001; Böhm et al., 1999). However, both the very large number and the locally very different needs and threats to flooding are insufficient conditions for homogenous river basin related flood management in spatial planning on the municipal level. Co-operation on this level is more driven by local interests than an integrated approach aimed at mutual support for catchment wide improvements in spatial planning. Due to the conditions named above the municipal level is not suitable as decisive framework for the development of common approaches and for the negotiation of measures or mutual compensation.

From the characterisations of levels it can be concluded that

- the transnational and national level is suitable for giving targeted performance specifications but that these bodies are not suitable for further concrete realisation
- the local level has competence only for areas which are too small to permit a successful river basin-wide agreement process.

Therefore, it is the regional level which is deemed most suitable for the tasks at hand. The co-operation structure developed is based on a voluntary union of regional government units. In almost all European countries, they fulfil a series of criteria which are required for the desired co-operation partners:

- they are small enough and they are in close contact with the population
- they have got competencies for spatial planning at the regional level and direct the municipal planning (exception: e.g. France)
- they have got responsibility for regional water management with competence in flood protection (exception: e.g. The Netherlands).

Thus, the interregional co-operation ('Flood risk management alliance') for preventive flood management should be an institutionalised co-operation with participants (authorities, organisations, public) from planning fields above the local and below the national level in (transnational) river catchment areas. The goal of the co-operation is the reduction of the flood risk and the assistance in the realisation of flood protection goals set in overall strategies, perspectives or action plans.

3.2. Actors for Co-operation

According to the approach developed the basic members of the co-operation 'Flood risk management alliance' are spatial planning authorities of the regions in the river catchment. They are the 'key actors' for the preparation of long term strategies and the implementation of flood protection regional planning. Other partners within the co-operation are representatives of the

- regional water management administrations
- other expert regional administration bodies such as nature conservation or waterways
- superposed spatial management authorities
- non-government organisations (NGO)
- municipalities.

As described above, the co-operation area should include the complete river catchment area, i.e. both the area along the main river itself as well as on the tributaries and their catchment areas.

3.3. Operating and Promoting Aspects of Co-operation

Due to the large volume of potential co-operation partners, it is obvious that smaller sub-units ('clusters') must be formed to produce concrete results and to negotiate co-operation benefits. A clear clustering following the similarity principle is recommended (example for the Rhine catchment see Figure 3):

- regions directly along the main river ('1st level regions')
- regions aside the main tributaries ('2nd level regions')
- other regions in the river catchment area ('3rd level regions').

One requirement for any successful co-operation is the development of trust and the building up of partner relationships. As a basic structure for the intended co-operations this clustering would bind the participating partners together in working groups.

The co-operation structure developed foresees the foundation of a union on the basis of a contract, with a public legal body designating the tasks, financing, structure and work programme for the first two years. A central office, as well as regular meetings of the participating groups with permanent designated representatives of the above mentioned regions, are necessary (see Figure 2). The concept

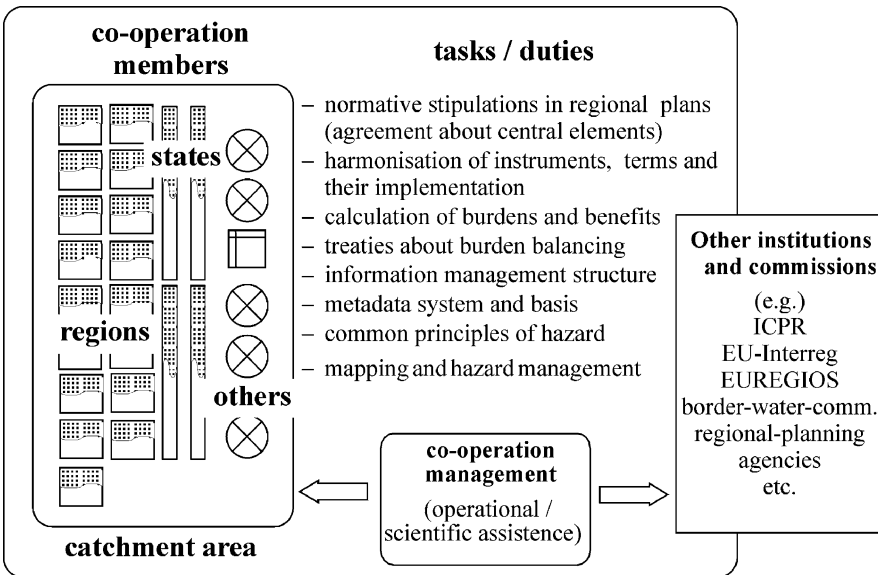


Figure 2. The recommended 'Flood Risk Management Alliance' in spatial planning (Böhm et al., 2001)

envisages an overall working group, as well as areal and expert subject clusters and a central co-operation management office.

Numerous criteria must be observed in the choice of a suitable legal form, e.g. the possibility of making contracts, national differences in the planning and legal systems, trustworthy regional co-operation forms, take-over of sovereign rights (see [Spannowsky, 1999](#), p. 17), as well as necessary or existing international agreements.

Experiences have shown that one of the most important operational aspects of co-operations is the necessity to set up a central operating office and a co-operation management, which is available to carry out the detailed structuring of the on-going workload and, which is responsible for the scientific and technical processing of questions which arise.

3.4. Support by Economic Incentives and Financial Compensation

The task of preventive flood protection presents a classical upstream-downstream problem scenario. The benefits, costs and other burdens of preventive actions to lower the discharge peaks are in different geographical locations and, as a rule, also affect different interest and actor groups.

The current principles of financing flood protection measures by the countries themselves do not provide for any compensating effects between diverging costs and benefits in transnational river basins and do not include the use of incentives.

Financial compensation as an equalisation payment for direct or indirect costs can be made either as a legal obligatory payment or as a voluntary performance. Incentives, in contrast to financial compensatory performance or payments in kind, are not designed to directly compensate for costs which can be defined in money terms but they are rather an offer designed to increase the acceptance of (usually indirect) burdens. The nature of the offer must not necessarily be directly connected to the cause of the burdens which have occurred. The volume of the incentive – in contrast to compensation – cannot be calculated with a neutral formula. As a rule, it is the result of negotiations. Agreements involving the provision of incentives are not based on legal regulations but they are agreed in an informal manner.

Economic incentives and financial compensations should

- strengthen the principle of the ‘causer pays’ for future uses in flood plains
 - create incentives for local/regional measures by providing compensation for disadvantages
 - be based on the interconnections between measures and effects, including cost sharing
 - create the acceptance for a higher level of transparent negotiations and processes.
- The calculation of the compensation offer to internalise external benefits follows the principle (see [Table II](#)):

$$\text{compensation offer} = \text{benefits}_{\text{extern}} - \text{costs}_{\text{extern}} - \text{benefits}_{\text{intern}}$$

Table 1. Calculation of the compensation offer from benefits and costs (Böhm et al. 2001)

Benefits for downstream actors (= extern benefits)	
+	• Reduction of damage potential (municipalities / private / companies / agriculture) • Saved costs for maintenance (dikes e.g.)
Costs for the measure at the place of construction (= external costs)	
–	• Acquisition of land • Costs for planning and constructions • Landscape and renaturalisation • Compensation for farmers or affected infrastructure
Indirect benefits at the place of the construction (if possible for calculation) (= intern benefit)	
–	• Revitalisation of meadow lands • Improvement of the tourism and recreation qualities / Promotion for regions
= (result:) Compensation offer of downstream region and responsables to affect local actors (if positive)	

The decisive factor is the willingness of the downstream areas to actually offer and pay some of their potential savings to the upstream areas – and on the other side – the willingness of the upstream regions to accept disadvantages for their land use in the meadow lands (effective only in large scale) by getting paid for their burdens.

Particularly on this point there is much room for negotiation because the potential savings only represent a part of the overall costs. The definition of a reducing factor is important to accomplish agreement. This represents the willingness of downstream regions to pay for the reductions of potential damage by upstream measures. Examples show that the sums offered are much lower than the theoretically calculable value of the expected damage reduction. All in all, the principle of burden sharing between the beneficiaries and those affected represents a necessary further development in financing practice which – in view of the large financing volumes – in the long term, cannot be oriented towards subsidising funds alone.

To succeed in the approach to support regulatory water management and spatial planning instruments by economic instruments, which can encourage the initiative of upstream regions, it is necessary to:

- develop an integrated co-operation of responsible actors both of regional spatial planning and water management (see above)
- reduce still existing reservations between actors from upstream/downstream and the views of ‘do not believe in upstream measures, better help yourself’
- evaluate the limits of the willingness to pay for risk reduction and to accept measures in relation to the compensation offers
- calculate (theoretical) compensation offers for single measures
- start negotiations (by an institutional co-operation; neutral mediators)
- examine and, where appropriate, change international law to reduce the problems of interregional transnational agreements.

4. PRESENT STATE AND VISIONS IN LARGE EUROPEAN RIVER BASINS

4.1. Co-operation in the Rhine Catchment

In the past, in the Rhine catchment area different co-operation forms between participants of spatial planning and other partners have developed. However, preventive flood management plays, in most institutionalised transnational co-operations, which are rather spatial planning or regional planning orientated, no or only a temporary, rather coincidental role. Three co-operations exist, in which flood protection is the only goal or one of the most important (see Figure 3).

At transnational level, some decades of successful international efforts have led to an institutional co-operation (International Commission for the Protection of the Rhine – ICPR) which has set ambitious goals for preventive flood protection agreed upon by the national governments (Action plan for the Rhine: [ICPR, 1998](#)). Members of the commission are high-ranking officials of the member states from the national and regional water management authorities as well as individual representatives of national planning authorities. Representatives of regional spatial planning

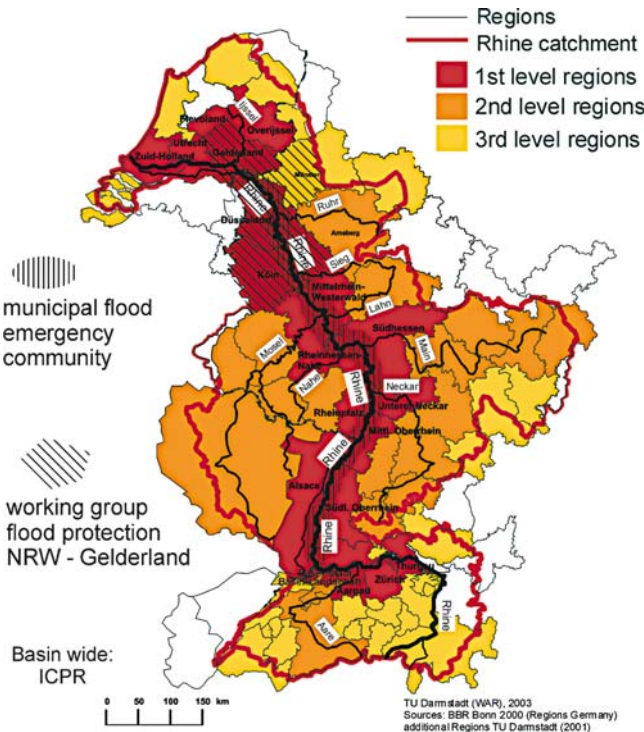


Figure 3. Rhine catchment: Recommended versus existing co-operation structures with an orientation towards spatial planning and flood risk

are not appointed to the ICPR – commission. Because of the missing regional representation negotiations on compensation offers and incentives between regions cannot take place¹

Activities primarily focus on the main river course. Execution instruments, besides international-law self obligations (international contracts) do not exist. Therefore, the implementation of suitable measures is again dependent on the national and regional levels of water management and spatial planning. Accordingly, the results vary compared to the aims of the action plan. Most intermediate objectives of the action plan were reached until the year 2000, but the goal to not increase damage potential was missed (ICPR, 2001, p. 4). Thus, an effective land use control in risk areas behind the dykes cannot be carried out by the ICPR. However, the ICPR can be evaluated as an important framework for future development of co-operation in spatial planning in the Rhine basin.

The German-Dutch working group for flood protection (North Rhine-Westphalia/Germany and Gelderland/the Netherlands) was established at Ministerial level after the extreme flood of 1995. Concrete binding agreements are not the original goal of the working group, which was not legitimised for that. Among others, the main objectives are mutual information with informal coordination of projects and planning standards of protection, as well as developing the simulation programs (van de Nes, 1999, p. 72; German-Dutch working group flood protection 1997, p. 5). The extension of co-operation by further entry of other regions from the Rhine catchment area is desired (Kamminga, 1999, p. 6).

The *Hochwassernotgemeinschaft Rhein e.V.* (Rhine Flood Emergency Community) is a transnational union at municipal level comprising municipalities along the entire river. The emergency community works as an interest agency for municipalities. For example, it may try to increase the acceptance for upstream measures. The emergency community is a good example of the co-operation of upstream and downstream actors. It is an important functioning structure for flood protection on the Rhine. However, it only has a small influence on interregional planning processes and does not have a mandate for negotiations nor authority for flood protection planning. Furthermore, it does not cover the whole river catchment.

Apart from the co-operations acting on the transnational scale, various co-operations for flood risk management exist within national boundaries. Examples are the regional clusters defined in the Netherlands within the framework of the IRMA programme (van Venetie, 2000; IRMA, 2000) or the ministerial working group for flood danger mapping in Baden-Württemberg (Germany). However, these co-operations are limited to national boundaries and have no legal or formal structure. Furthermore, they do not fulfil the requirements of the long-term interregional approach as described above.

¹ Even though the Upper Rhine contract obliges these regions to compensate for lost retention areas – following the causer must pay-principle – it does not provide for compensation offers, including benefits of downstream regions and burdens of upstream regions.

From a different angle, the impacts of the European Union Regional Development programmes (IRMA 1998–2001, INTERREG IIIB 2000–2006) will now be addressed. These programmes are distinctly designed to integrate spatial planning and flood protection. However, long-term strategies cannot be carried out as their promoting impact is limited in time. These financial subsidies could support long-term strategies through better co-ordination amongst actors. There is a need to better integrate local and regional decision-makers into the programmes, as they have the mandate of making land use decisions.

Up to date, a deficit of the co-operation structures in the Rhine catchment is recognised by the fact that there is no concrete interregional working level responsible for integrating those responsible for regional land use management into the whole river catchment area. So far the option of partly financing the development of such structures by Community Initiatives has not been seized. As a rule, partners of INTERREG IIIB flood management projects in the Rhine basin are water management authorities and other organisations, but up to date no project aims at integrating all relevant regions within the Rhine catchment.

In programmes such as IRMA, 78% of all funding was directed to regions in the lowland valley which obviously is the most affected region. However, in future, in the interest of all actors, larger parts of funding must be transferred to the central and upper catchment regions. In the Rhine basin, more than 80 % of the necessary expenses for flood protection measures will have to be spent in the upper and middle Rhine regions by 2020 (ICPR, 1998). To achieve this, self-reliance will not be enough, if no additional measures support such efforts. Either legally binding conditions or incentives could be used. Here, it becomes clear that interregional transaction could help.

In addition the linking of action plan targets and action priorities with the necessary financing is required, in the interest of all regions in the catchment area. Thus, upstream regions and those which benefit of upstream measures have to be linked by future financing strategies.

4.2. The Oder Catchment – Co-operation

Over the past decades and centuries, extreme flood events have often occurred in the Oder valley causing considerable damage. The most recent event, i.e. the summer floods of 1997, is still fresh in memory. The flooding and dam breaches caused enormous material damage – particularly in the Republic of Poland and the Czech Republic – and unfortunately in these countries there was loss of life as well (IKSO, 1999; Bronstert et al., 1999).

The ‘OderRegio Project – Transnational Conception for Preventive Flood Protection in the Oder Catchment Area’ has devoted itself to the task of achieving an integrated flood protection. The target of the project was to develop methods and priority actions in spatial planning for flood prevention in the Oder catchment area (Böhm, 2000; Neumüller, 2000; INFRASTRUKTUR & UMWELT et al., 2001).

The necessity of taking the complete river basin area into consideration is self-evident. The extreme flooding in 1997 showed that floods do not stop at national borders and that there are very important relationships between downstream and upstream areas. Flood protection on the Oder is thus a transnational task for the countries where this river flows i.e. the Czech Republic, the Republic of Poland and the Federal Republic of Germany. The international commission for the protection of the Oder is working on a transnational action plan to outline a framework for water management tasks.

To meet this international challenge of integrating spatial planning and water management, in order to carry out the OderRegio project, the most important water management and spatial planning actors from national and regional levels from all three countries agreed to work together in a co-operative process. In a working group accompanying the project, more than 30 actors were involved. Here, intermediate results of fact finding and of potential and effect analysis were presented and discussed. Enormous benefits for the realisation of the OderRegio project were achieved through the active contributory work and co-operation of the participants, the inclusion of their expertise and local knowledge provided. National investment programs such as the Polish 'Program for the Oder – 2006' were also integrated into the project (Zaleski, 2000).

The result has been the successful production of a 'Conception for Preventive Flood Protection', which has been transnationally agreed on. In this conception, general principles and targets of preventive flood protection are formulated. Moreover, on the basis of the analyses carried out, concrete action recommendations for partial areas were made.

So far the following results have been achieved:

- a) A robust working structure has been created,
 - which is formed by representatives from national and regional level administrations from Germany, Poland and the Czech Republic
 - in which both the spatial planning and regional planning, as well as water management are represented
 - which guarantees agreement with the work of legitimate initiatives such as the 'Stettiner Initiative' and the International Commission for the Protection of the Odra River against Pollution (ICPOAP).
- b) General fundamental principals and targets of spatial planning for preventive flood protection in the catchment area of the Oder have been defined and agreed on.
- c) These fundamental principles and targets were concretised for individual partial areas (areas of action) and corresponding action requirements were named.
- d) The results have been included in the consultations of the 'Stettiner Initiative' (signature of a declaration by the responsible ministers for spatial planning from the Czech Republic, the Republic of Poland and the Federal Republic of Germany on 29th June 2001) and in studies for the draft 'Action Program Floods' of IKSO (compare IKSO, 2001).

Thus, the OderRegio project provides an important contribution to a trinationally agreed and integrated action program for preventive flood protection in the Oder catchment area. However, until now the agreements do not affect the planning at regional and local level. To include the regional level, basin-wide, into the implementation, a second project phase OderRegio part-financed by INTERREG IIIB programme was set up to be executed from 2003 until 2006.

4.3. Developments in the Elbe River Basin

The flood events in the Elbe catchment of 2002 showed, dramatically, that flood prevention and common management approaches have to be improved, in particular regarding long term spatial planning. Like in other river basins, an action plan for flood defence was drafted in summer 2002 by the International Commission on the protection of the Elbe (ICPE) but had to be revised after the flood. The revised version was agreed on at the end of 2003.

The Elbe basin is characterised by a very heterogeneous structure of authorities, commissions, working groups and planning groups of all different groups of actors, at all levels, transnational, national, regional, local. Driven by this, the idea was created to develop the INTERREG III B project ELLA ('Elbe-Labe flood management measures by transnational spatial planning').

The extraordinary challenge of the ELLA project is the transnational co-operation of nearly all regional spatial planning authorities in the Elbe basin. This unique comprehensive partnership covers almost the whole catchment area of the Elbe. Thus, the aims of EU water policies and the EU spatial planning perspective can be obtained under this INTERREG III B project. National and regional partners that are responsible for spatial planning, water management and agriculture assure that the far reaching integrated transnational approach will be implemented in many different regions at the same time.

The added value of the INTERREG – ELLA project is, that none of the regions would be able to achieve as extensive improvements in risk prevention as they do in the common INTERREG approach. Especially with view to the enlargement of the EU in 2004, an important brick for an adjustment of the planning strategies and policies in the field of risk prevention in the Czech Republic, Germany, Poland, Hungary and Austria will be delivered in ELLA. For positive development of economically disadvantaged risk areas, information on risk, improvements of safety standards and adapted land use planning will be achieved.

The intended ELLA – results are:

- Production of transnational strategic planning maps for the entire river basin.
- Exemplary improved regional plans, regional strategies, etc., following the transnational needs.
- An efficient transregional network of authorities regarding spatial planning and flood management.

- A transnational strategy for burden sharing incentives (compensation funds, negotiations).
- Risk maps ('Atlas'), agreement on retention measures, land use options (e.g. agriculture, forestry).

The ELLA project was granted by the Programme secretariat at begin of 2004 and will run until summer 2006. It is foreseen to evaluate the role of funds, with view to the willingness to co-operate in the river basin. Results can be expected in 2006.

In the first period, the co-operation will be based on a voluntary working basis ruled by a joint convention, which will direct the co-operation processes and which is necessary for the INTERREG project according to the EU regulations. But for the time being it is not planned to build up a new co-operation institution. Experience and accompanying evaluation will grade clearly the strength and weakness of the voluntary approach. Conclusions will lead to continuation or changes. This will be in 2006/2007.

5. CONCLUSIONS

Activities of spatial planning are necessary contributions to all flood risk management approaches since land use regulations are an important component of risk mitigation. Decisions on land use options in river valleys with dense population usually follow many competing stakes of different actors and are affected by local and economical interests. Preventive measures with precautionary effects for downstream regions suffer from missing acceptance, information and incentives. Thus, river basin wide co-operation can support the progress towards sustainable flood management strategies.

The status of the three compared approaches on co-operation in the three river basins of the Rhine, the Oder and the Elbe are too different to draw final conclusions yet. While the co-operation within the Rhine catchment has grown over nearly two decades, the Oder basin co-operation on concrete questions of flood management started only a few years ago. In the Elbe basin the building-up of structures has begun and is not yet finished. However, in all basins important lessons have been learned which can be summarised as 'interim conclusions' in the most cases. Table 2 gives an overview about characteristics and differences between the co-operation structures and results.

Especially until today, the starting phases have been evaluated by comparing the three basins. From this comparison, crucial criteria for the starting phase can be deduced:

5.0.1. *Initiation*

The initiation process is the first important step towards the establishment of co-operation structures. In all cases, it has been initiated by stakeholders or regional planning authorities (in the Elbe basin accompanied by a national authority) who are situated in the downstream areas of the river basins. This seems logical since

Table 2. Comparison of co-operation structures in the Rhine, Oder and Elbe basins

criteria / requirements	Rhine	Oder	Elbe
Co-operation structure			
Co-operation levels	National or local level	National, regional (local levels planned)	National, regional
Spatial coverage	Basin wide only in water management	Basin wide	Basin wide
Working clusters	Partly for defined tasks, e.g. risk mapping along the main river	Aimed at until 2006	Aimed at until 2006
Members with responsibility for spatial planning	Only sporadic integration, mostly national level	At national and partly regional level regional level aimed at in 2006 (exemplary)	Aimed at on national and regional level until 2006 (partly)
Basin wide co-operation structure	Institution ICPR for water management; regional spatial planning not included	Institution ICPO for water management; regional spatial planning not included Spatial planning: Joint INTERREG-project ICPO contract between river basin states. INTERREG: Joint convention of partners (voluntary)	Institution ICPE for water management; regional spatial planning: Joint INTERREG-project ICPE contract between river basin states. INTERREG: Joint convention of partners (voluntary)
Level of institutionalisation	ICPR: contract between river basin states	ICPO contract between river basin states. INTERREG: Joint convention of partners (voluntary)	2 National and regional partners
Initiator	Different stakeholders in water quality de-bate (farmers, fishery)	1 Regional partner	
Tasks and goals			
Harmonisation of instruments, terms and their implementation	Mainly for the main river course, not the whole catchment, strategies at national level, no concrete implementation on regional level	Focus is on implementation; enquiry on legal harmonisation possibilities.	Comparison, joint conclusions for the river basin; enquiry on legal harmonisation possibilities.
Calculation of burdens and benefits	No	No	Aim
Basis for upstream – downstream negotiations	No, except ‘causer must pay principle’ (Upper Rhine)	Negotiations on precautionary measures; incentives or compensation not foreseen yet	Not clear enough yet
Hazard information base	Existing for most part of the basin; for main tributaries until 2010	Very general for the Oder; planned for the rest of the basin.	Not existing; planned for parts of the Elbe river by 2006

downstream regions aim at benefits from co-operations more than upstream regions. In the Oder and the Elbe basin, it was possible to start the coordination and co-operation through continuous intensive contacts and negotiations about possible benefits. The important lesson learned is that without great efforts of downstream actors, a robust basis for effective co-operation structures cannot be developed even though it is the request of European policies like the European Spatial Development Perspective (ESDP).

5.0.2. *Importance of mutual confidence and slowly growing networks*

It is decisive for the success of a co-operation to follow significant steps in the right order together with all partners at the right pace. Clear structures are needed from the coordination phase onwards. All three examples have underlined existing earlier experiences of regional and interregional co-operations, that much time is needed before first benefits of the co-operation can be expected. In the Rhine basin the co-operation in flood management issues is based on earlier networks of water management authorities and spatial planning authorities that have grown over years. The International commission for the protection of the Rhine is an example of effective co-operation over the decades, even if the real benefits for water quality were only experienced after 20 years. The examples of co-operation also confirm that 'natural' steps have to be made in the right order and that speeding up the development phase is not sensible for enhancing the quality of the co-operation. The steps are (acc. to Frey, 2001, p. 4):

- (no co-operation)
- information
- consultation
- coordination
- co-operation
- integration.

There is also evidence in the examples that at least two stages are necessary in building up the co-operations: the first one should aim only at an agreement on goals and strategies. The second should focus on concrete measures.

5.0.3. *Range of autonomy*

The co-operations in the Oder and the Elbe basins are based on voluntary networks with a very wide range of autonomy. The joint work follows a framework of funding programmes for and joint conventions about the co-operation. However, further regulations or policies do not limit the autonomy of the single partners. The importance of this framework for the effectiveness of the co-operations can not be proved yet. But it can be stated that the start of the co-operations with transnational networks in Germany, Poland, and Czech Republic etc. would not have been possible if a transfer of planning responsibility would have been an obligatory part of the joint conventions. Another criterion is the autonomy of the co-operation structure against other national authorities. This cannot clearly be rated for Oder and Elbe. But for the Rhine, Durth (1996, p. 202) attributes the great

successes of the ICPR in water pollution reduction to the fact that the ICPR had a considerable autonomous range of action at its disposal and also used this. This means that the co-operation and its central office can only act on the instruction of its members through their representatives in the plenary session. The decisions are made by the representatives in the plenary session. At the same time, however, the members themselves must be obliged in the co-operation agreement to fulfil and/or abide by these decisions.

The overall perspective of interregional and transnational co-operation in the evaluated river basins demonstrates reasonable developments for positive long term improvements. To overcome the bottlenecks described, dedicated promoters, sufficient flow of information and the political will to collaborate even if local concessions have to be made, are essential. It is a slow but gradual process, which hopefully continues even without great flood disasters to remind of its need.

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