GLOBAL IGBP CHANGE

THE IGBP SERIES

LOICZ

C. J. CROSSLAND
H. H. KREMER
H. J. LINDEBOOM
J. I. MARSHALL CROSSLAND
M. D. A. LE TISSIER
Editors

Coastal Fluxes in the Anthropocene




Springer

Global Change – The IGBP Series

Christopher J. Crossland · Hartwig H. Kremer · Han J. Lindeboom
Janet I. Marshall Crossland · Martin D. A. Le Tissier

Coastal Fluxes in the Anthropocene

The Land-Ocean Interactions in the Coastal Zone Project of the International Geosphere-Biosphere Programme

With 121 Figures

Springer

Editors

Christopher J. Crossland

Centre of Marine Studies
The University of Queensland, Brisbane, Australia

and
Institute for Health, Sustainability and Regional Engagement
University of the Sunshine Coast, Queensland, Australia

Hartwig H. Kremer

LOICZ IPO
Royal NIOZ, Texel, The Netherlands

Han J. Lindeboom

Alterra
Royal NIOZ, Texel, The Netherlands

Janet I. Marshall Crossland

Yaroomba, Queensland, Australia

Martin D. A. Le Tissier

LOICZ IPO
Royal NIOZ, Texel, The Netherlands

Library of Congress Control Number: 2005926496

ISSN 1619-2435
ISBN-10 3-540-25450-1 **Springer Berlin Heidelberg New York**
ISBN-13 978-3-540-25450-8 **Springer Berlin Heidelberg New York**

Springer is a part of Springer Science+Business Media
springeronline.com

Printed in Germany

Cover design: Erich Kirchner, Heidelberg
Typesetting: Klaus Häringer, Büro Stasch · Bayreuth (stasch@stasch.com)
Production: Luisa Tonarelli
Printing: Stürtz AG, Würzburg
Binding: Stürtz AG, Würzburg

Printed on acid-free paper 32/2132/LT – 5 4 3 2 1 0

Preface

In an ever-changing world, the global coastal zone stands out as an area of extraordinary changes. These changes are shaped by natural processes and phenomena that influence the Earth systems – on land, in the ocean, in the atmosphere, at their interfaces and at planetary scales – and ensure a dynamic coastal environment that has continued to respond and adapt biologically, physically and chemically in unique ways. Now there is a greater catalyst for change in the coastal zone – human society – impacting directly on coastal processes and systems and indirectly through modification of the natural processes and events.

The world's coastal zone is a long narrow feature of mainland, islands and adjacent seas denoting a zone of transition between land and ocean. Humans have lived in the coastal zone for millennia utilising its many and rich resources for their survival and socio-economic benefit. The coastal zone is the area where 25% of global primary productivity occurs, and it supplies about 70% of global fish catch. Some 50% of the people in the world live in this relatively small but highly productive, highly valued and highly dynamic domain which occupies 12% of the surface of the Earth. The density of coastal populations varies dramatically among different coastal regions, and there is a general trend of people moving from inland regions to the coast. The richness and diversity of resources found in coastal areas has long been recognised by humans, and there has been a corresponding concentration of human activities and settlements along shorelines and estuaries throughout the world. It is clear that the coast will continue to sustain the livelihoods of a very large proportion of the human population, both those living there and those living inland. The coastal zone is therefore an important asset to people worldwide.

At the same time, the coastal zone is a domain of constant change and one of the most threatened areas on Earth. Changing wave and current regimes, climate, morphological processes and fluxes of materials between land, atmosphere and oceans are causes of high natural variability which is still imperfectly understood. In the last several decades, with their increasing technological capabilities, humans have accelerated the rate of change and increased their influence on already highly variable ecosystems (Steffen et al. 2004). Pollution, eutrophication, changing sediment load, urbanisation, land reclamation, overfishing, mining and tourism continuously threaten the future of coastal ecosystems. Impacts on the coastal zone originate locally, regionally and globally, and an understanding of these impacts is now obligatory within the context of global change, including climate change. Although most impacts are addressed at local and regional levels, the scale of development and population growth along all coasts of the world is increasing such that it has become a truly global issue. Despite the rapidly increasing knowledge about coastal ecosystems, crucial questions on the causes of natural variability and the effects of human impacts are still unanswered. Although the perception of environmental managers of our coasts is shifting from one of mainly short-term economic approaches towards long-term economic, ecological and sustainable perspective, the need for this shift in management practice is often ignored or difficult to communicate to policy-makers. In particular there is a widespread ignorance among coastal stakeholders of the multiplicity of temporal and spatial scales across which coasts are affected including the continuum from river catchment to the coastal ocean (Meybeck and Vogler 2004). The major challenge that we face today is managing the human use of coastal habitats so that future generations can also enjoy the many visual, cultural, edible products and sustainable resources that they provide.

Sustainable use and protection of the Earth's coastal areas are now items high on international agendas. The increasing international instruments, such as the United Nations Convention on the Law of the Seas (UNCLOS), Rio Agenda 21, and the Conventions on Wetlands, Biodiversity and Desertification provide important mechanisms for coastal management.

The need for increased knowledge about global change and its ramifications for the functioning of Earth systems motivated the establishment by the International Council for Science (ICSU) in the late 1980s of the global research initiative – International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) which aims "*to describe and understand*

- *the interactive physical, chemical and biological processes that regulate the total Earth system,*
- *the unique environment that it provides for life,*
- *the changes that are occurring in the system, and*
- *the manner in which they are influenced by human actions.*" (*http://www.igbp.kva.se*)

The Land-Ocean Interactions in the Coastal Zone (LOICZ) project was established in 1993 as one of eight core projects of IGBP, and was directed to provide scientific information to answer the IGBP core question: "*How will changes in land use, sea level and climate alter coastal ecosystems, and what are the wider consequences?*"

Fundamental to answering this question is the need to recognise that the coastal zone is not a geographic boundary of interaction between the land and the sea but a global compartment of special significance, not only for biogeochemical cycling and processes but increasingly for human habitation and economies. Also, the spatial and temporal heterogeneity of the world's coastal zone is considerable. Consequently, challenging methodological problems are associated with developing global perspectives of the role of the coastal zone compartment in the functioning of the Earth system. Clearly, a useful and practical knowledge of the globally heterogeneous coastal zone depends on harnessing an array of research from natural and social sciences and integrating with those both anthropocentric and geocentric forces of change. The LOICZ project is designed to encompass these elements in providing science information to the global community, which should then be of use to decision-makers and coastal zone managers globally.

The LOICZ Science Plan (Holligan and de Boois 1993) developed four overarching objectives to address the IGBP question:

1. To determine at global and regional scales: the fluxes of materials between land, sea and atmosphere through the coastal zone, the capacity of coastal systems to transform and store particulate and dissolved matter, and the effect of changes in external forcing conditions on the structure and functioning of coastal ecosystems.
2. To determine how changes in land use, climate, sea level and human activities alter the fluxes and retention of particulate matter in the coastal zone, and affect coastal morphodynamics.
3. To determine how changes in coastal systems, including responses to varying terrestrial and oceanic inputs of organic matter and nutrients, will affect the global carbon cycle and the trace gas composition of the atmosphere.

4. To assess how responses of coastal systems to global change will affect the habitation and usage by humans of coastal environments, and to develop further the scientific and socio-economic bases for the integrated management of coastal environments.

These objectives, however, do not imply that LOICZ is actively undertaking coastal zone management, but rather it is providing knowledge and tools that underpin options for alternatives in development and decision-making. A clear goal is to provide a sound scientific basis for future sustainable use and integrated management of the components of coastal environments, under conditions of global change.

Following consultation with scientists globally, the LOICZ Implementation Plan (Pernetta and Milliman 1995) identified the array of issues and science that needed to be addressed, recognising the large (and somewhat prohibitive) funding requirements for a global coastal research programme. Operationally, LOICZ focussed on gaining an understanding at global scales of the following questions:

- Is the coastal zone a sink or source of CO_2?
- What are mass balances of carbon, nitrogen and phosphorus in the coastal zone?
- How are humans altering these mass balances, and what are the consequences?
- What is the role of the coastal zone in trace gas (e.g., DMS, NO_X) emissions?
- How do changes in land use, climate and sea level alter the fluxes and retention of water and particulate matter in the coastal zone and affect coastal morphodynamics?
- How can knowledge of the processes and impacts of biogeochemical and socio-economic changes be applied to improve integrated management of the coastal environment?

For the last decade, LOICZ has addressed these questions by focussing on horizontal material fluxes and scaling of processes through the application of environmental and socio-economic sciences. These activities have used results from research programs and contributions of individual scientists, and LOICZ has built a large network of researchers across more than 80 countries to develop collaborative and interdisciplinary projects to meet the goals outlined in the LOICZ science plan and implementation strategy.

This book provides a synthesis of the LOICZ work during its first decade ending 2002. It represents a milestone rather than a destination for the journey of collaborative inquiry into material fluxes and human interactions in the coastal zone. While compilation of the individual chapters have been the responsibility of the identified authors (see Authors and Contributors), the overall work represents an enormous amount of effort and research by many thousands of scientists who have contributed to the LOICZ enterprise. Some of these many contributions are found in LOICZ publications from workshops that have addressed regional and thematic coastal science (see Appendix A.1) as well as in the wider scientific literature.

This book addresses key elements of material flux in the coastal zone and indications of change, then draws together the biogeochemical information with an assessment of the influence of human society, before looking at future needs for targeted research and management actions in the coastal zone.

Chapter 1 provides a description and operational definition of the coastal zone. By discussing its spatial and temporal heterogeneity and natural variability, the authors differentiate between variability and change, and consider the dynamics of human population as a forcing factor for change. Changes in the intensity and extent of human drivers and pressures for change are outlined, along with a consideration of economic valuation of coastal resources and services. The challenges in assessing change at global scales and the approaches taken by LOICZ are presented, especially the new tool of typology.

Chapter 2 addresses the dynamics of a changing coastal boundary. Projections in sea level fluctuation are reviewed along with the implications for changed coastal and shoreline vulnerability. Changes in sediment and water fluxes to the coastal sea are undergoing major changes. The magnitude of the changes and their ramifications on coastal and estuarine morphologies are highlighted, noting especially the role of dams and reservoirs, other water impoundments and coastal water extraction. Submarine groundwater discharge is discussed, including new methods for assessment, the biogeochemical implications of these fluxes and the need for improved understanding and appropriate management of this regionally important freshwater resource.

Chapter 3 examines the biogeochemical fluxes of nutrients, especially carbon, nitrogen and phosphorus transport and transformations, within the coastal zone. The question of whether the coastal zone is a source or sink for carbon is examined. The role of estuaries and coastal seas as "incubators" of inorganic nutrients is assessed, including a system's capabilities as a region for net nitrogen gas release or retention. New estimates of inorganic nutrient discharge from river catchments are derived that show significant changes in loads to the coastal seas within the last 30 years. The typology approach developed by LOICZ is used to aggregate the many estimates of metabolic performance by relatively small-scale estuarine and coastal sea ecosystems to achieve global measures of nutrient and net metabolic changes, especially those related to nutrient discharges from the land.

Chapter 4 develops a broad picture of river catchment drivers and pressures and their impacts on coastal change. Where available, information on related governance response is provided. By looking at the river catchment-coastal sea continuum as a single system, the authors address individual catchment assessments and extrapolate information to regional or continental scales. Coastal change issues and related drivers are ranked, based on mostly qualitative information, including the identification of critical loads and thresholds for system functioning or geomorphologic stability. The regional difference in the relative role played by specific drivers in imposing coastal change, such as damming, intense agricultural, land use and urbanisation, are highlighted and expected trends are identified.

Chapter 5 provides a synthesis of major scientific findings determined in the first four chapters. It addresses the "So What?" relevance question by considering the ramifications of the findings for policy- and decision-makers involved in governance and management of the coastal zone. In so doing, the authors provide a glimpse of the remaining challenges and future directions for the next decade of LOICZ activities and the wider coastal community.

Text boxes have been used throughout the book to give both details on methodologies and examples of case studies which are referred to in the text. The Appendix includes a list of key LOICZ publications and abbreviations to assist the reader.

The LOICZ project is continuing into a second phase within IGBP, building on the findings and gaps identified here and responding to a new priority of issues that have emerged from discussions engaging the global scientific community and institutions. The new project has shifted in focus towards highlighting the societal and environmental management dimensions of coastal material fluxes (LOICZ II Science Plan and Implementation Strategy; *http://www.loicz.org*). LOICZ is expected to become the major contributor of interdisciplinary coastal science to the second stage of the IGBP and the International Human Dimensions Programme (IHDP), and to the Earth System Science Partnership of IGBP, IHDP, WCRP and DIVERSITAS.

Han Lindeboom

Chair, LOICZ Scientific Steering Committee 1997–2003

References

Holligan PM, de Boois H (eds) (1993) Land-Ocean Interactions in the Coastal Zone (LOICZ) – science plan. IGBP global change report. International Geosphere-Biosphere Programme, Stockholm, No. 25

Meybeck M, Vogler J (2004) Bridging gaps between conventional views on river coast systems In: River/Coast integration in European regional seas, Part 1: improving basin coast integration, EuroCat work package 5.3. European catchments, catchment changes and their impact on the coast, EuroCat, Final Report. European Commission, DG Research, 5th Framework Programme, Contr. No. EVK1-CT-2000-00044), pp 28–48

Pernetta JC, Milliman JD (1995) Land-Ocean Interactions in the Coastal Zone – implementation plan. IGBP global change report. International Geosphere-Biosphere Programme, Stockholm, No. 33

Steffen W, Sanderson A, Tyson P, Jager J, Matson P, Moore III B, Oldfield F, Richardson K, Schellnhuber H-J, Turner II BL, Wasson R (2004) Global change and the Earth system: a planet under pressure. IGBP global change series. Springer-Verlag, Berlin, Heidelberg

Acknowledgements

The government of the Netherlands (Ministry of Education, Culture and Science, OcW NWO; Ministry for Transport and Public Works, RIKZ) has generously provided funding support for the LOICZ International Project Office over the last 10 years; the Royal Netherlands Institute for Sea Research (KNIOZ) has provided offices, scientific and administrative support for the IPO. Without this funding the international Scientific Steering Committee and the vital network of collaborating scientists could not have functioned. Acknowledgment is made to the many international and national organisations and agencies that have funded and supported the LOICZ enterprise described in this book, in particular: UNESCO's Intergovernmental Oceanographic Commission (IOC), United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF), the European Union (EU), Netherlands Foundation for the Advancement of Tropical Research (WOTRO), Royal Dutch Academy of Science (KNAW), Scientific Committee for Oceanic Research (SCOR), United States National Science Foundation (NSF), Asia-Pacific Network for Global Change (APN), Global Change System for Analysis Research and Training (START), Inter-America Institute for Global Change (IAI), and International Ocean Institute (IOI).

The preparation of this book has involved many people beyond the authors and editors in keeping with the networked and collaborative approach engendered within the LOICZ project. In particular, the work has benefited from the skilled services of Hester Whyte (LOICZ IPO) and Nelleke Krijgsman (KNIOZ) in the management and completion of the manuscript and associated graphics.

Valuable suggestions were contributed to drafts of the chapters by a panel of reviewers, including: Elena Andreeva, Franciscus Colijn, William Dennison, Goetz Floeser, Anthony T. Forbes, Alison Gilbert, Isao Koike, Felino Lansigan, Michel Meybeck, Alice Newton, Jozef Pacyna, John Parslow, Nancy N. Rabelais, Juan D. Restrepo, Eva Roth.

Permissions

Contents

Authors and Contributors

Elena N. Andreeva

Laboratory of Arctic Studies
Institute for System Analysis
Russian Academy of Sciences
9 Prospect 60-let Octyabria
117312 Moscow, Russia
VNIISI@isa.ac.ru

Russell K. Arthurton

Coastal Geoscience Consultant
Grimston, Leics, LE14 3BY, United Kingdom
r.arthurton@btinternet.com

Dan Baird

Zoology Department
University of Port Elizabeth
PO Box 1600, Port Elizabeth, Republic of South Africa
zladdb@zoo.upe.ac.za

Horst Behrendt

Forschungsverbund Berlin
Institut fur Gewasserökologie und Binnenfischerei
Müggelseedamm 310
12587 Berlin, Germany
behrendt@igb-berlin.de

Henry Bokuniewicz

Marine Sciences Research Center
Stony Brook University
Stony Brook, NY 11794-5000, USA
hbokuniewicz@notes.cc.sunysb.edu

Robert W. Buddemeier

Kansas Geological Survey
University of Kansas
1930 Constant Ave,
Lawrence, Kansas 66047, USA
buddrw@ku.edu

Peter R. Burbridge

The Orchard, House of Ross
Comrie, Perthshire PH6 2JS
United Kingdom
Peter_Burbridge@yahoo.co.uk

William C. Burnett

Department of Oceanography
Florida State University
Tallahassee, FL 32306, USA
wburnett@mailer.fsu.edu

Victor F. Camacho-Ibar

Instituto de Investigaciones Oceanológicas
Universidad Autónoma de Baja California
Ensenada, Mexico
PO Box 189003, Coronado 92178-9003, USA
vcamacho@uabc.mx

Janet W. Campbell

Oceans Processes Analysis Group, ISEOS
University of New Hampshire, Durham NH, USA
janet.campbell@unh.edu

Chen-Tung Arthur Chen

Institute of Marine Geology and Chemistry
National Sun Yat-sen University
Kaohsiung, Taiwan
ctchen@mail.nsysu.edu.tw

Lee Cooper

Department of Ecology and Evolutionary Biology
University of Tennessee
Knoxville, TN 37932, USA
lcooper@utk.edu

Robert Costanza

Gund Institute of Ecological Economics
The University of Vermont
590 Main Street, Burlington VT 05405-1708, USA
Rcostanz@zoo.uvm.edu

Christopher J. Crossland

Centre of Marine Studies
The University of Queensland
St Lucia, Brisbane, Queensland, Australia *and*
Institute for Health, Sustainability and Regional Engagement
University of the Sunshine Coast
Maroochydore DC, Queensland 4558, Australia
jcross@gil.com.au

Laura T. David

Marine Science Institute
University of the Philippines
Diliman, Quezon City 1101, The Philippines
ldavid@upmsi.ph

William C. Dennison

Centre for Environmental Science
University of Maryland
PO Box 775, Cambridge, MD 21613, USA
dennison@ca.umces.edu

Jean-Paul Ducrotoy

GEMEL
Universite de Picardie Jules Verne
115 quai Jeanne d'Arc, 80230
Saint Valery sur Somme, France
gemel.ducrotoy@tiscali.fr

Kenneth Dunton

Marine Science Institute
The University of Texas at Austin
Port Aransas, TX 78373, USA
dunton@utmsi.utexas.edu

Vilma D. Dupra

Marine Science Institute
University of the Philippines
Diliman, Quezon City 1101, The Philippines
vdupra@upmsi.ph

Jürgen Gandrass

GKSS-Research Centre
Institute for Coastal Research/
Physical and Chemical Analysis
Max-Planck-Straße
D-21502 Geesthacht, Germany
juergen.gandrass@gkss.de

Shu Gao

Department of Geo-Ocean Sciences
Nanjing University
Nanjing, China
shugao@nju.edu.cn

Vjacheslav V. Gordeev

PP Shirshov Institute for Oceanology
Russian Academy of Sciences
Nakchimovskyprospect 36
117997 Moscow, Russia
gordeev@geo.sio.rssi.ru

Vivien Gornitz

NASA Goddard Institute for Space Studies and
Columbia University Center for Climate Systems Research
New York, NY, USA
vgornitz@giss.nasa.gov

Nick Harvey

Department of Geographical and Environmental Studies
University of Adelaide
South Australia 5005, Australia
nick.harvey@adelaide.edu.au

Patrick P. Hesp

Department of Geography and Anthropology
Louisiana State University
Baton Rouge LA 70803-4105, USA
pahesp@lsu.edu

G. H. Hong

Marine Biogeochemistry and Isotopes
Korean Ocean Research & Development Institute
Seoul 425-600, Republic of Korea
ghhong@kordi.re.kr

Bjorn Kjerfve

Marine Science Program
University of South Carolina
Columbia, South Carolina 29208 USA
bjorn@msci.sc.edu

Joannie A. Kleypas

Environmental & Societal Impacts Group
Boulder, Colorado 80307-3000, USA
kleypas@ucar.edu

Luiz Drude de Lacerda

Instituto de Ciencias do Mar
Universidade Federal do Ceara
Fortaleza, 60125-120, Ceara, Brazil
ldrude@fortalnet.com.br

Laure Ledoux

CSERGE
University of East Anglia
Norwich, Norfolk NR4 &TJ, United Kingdom
l.ledoux@uea.ac.uk

Martin Le Tissier

LOICZ International Project Office
Royal Netherlands Institute for Sea Research
PO Box 59, NL-1790 AB Den Burg
Texel, The Netherlands
loicz@nioz.nl

Han Lindeboom

Alterra
Postbus 167, 1790AD Den Burg,
Texel, The Netherlands
h.j.lindeboom@alterra.wag-ur.nl

Janet I. Marshall Crossland

1499 David Low Way
Yaroomba, Queensland 4573, Australia
jcross@gil.com.au

Bruce A. Maxwell

Department of Engineering
Swarthmore College
500 College Ave, Swarthmore, PA 19081, USA
Maxwell@swarthmore.edu

Nicole Morcom

Department of Geographical & Environmental Studies
University of Adelaide
South Australia 5055, Australia

Eric Odada

Pan-African START Secretariat
Department of Geology, University of Nairobi
Nairobi, Kenya
pass@uonbi.ac.ke

Jozef Pacyna

Norwegian Institute for Air Research
NO-2027 Kjeller, Norway
jozef.pacyna@nilu.no

Gerardo M. E. Perillo

Instituto Argentino de Oceanografía
CC 804, 8000 Bahía Blanca, Argentina
perillo@criba.edu.ar

Nancy N. Rabalais

Louisiana Universities Marine Consortium,
Chauvin, Loiusiana, USA
nrabalais@lumcon.edu

Yoshiki Saito

MRE, Geological Survey of Japan
AIST. Tsukuba, Ibaraki 305-8567, Japan
yoshiki.saito@aist.go.jp

Joe Salisbury

Oceans Processes Analysis Group, ISEOS
University of New Hampshire
Durham NH, USA
Joe.Salisbury@unh.edu

Maria Lourdes San Diego-McGlone

Marine Science Institute
University of the Philippines
Diliman, Quezon City 1101, The Philippines
mcglonem@upmsi.ph

P. T. Sandhei

Kansas Geological Survey
University of Kansas
1930 Constant Ave, Lawrence, Kansas 66047, USA

Wim Salomons

VU-IVM
Kromme Elleborg 21, 9751 RB Haren
Groningen, The Netherlands
Wim.salomons@home.nl

Stephen V. Smith

Departmento de Ecologia
CICESE
Ensenada, Baja California, Mexico CP 22800
PO Box 434844 San Diego, CA 92143-4844 USA
svsmith@cicese.mx

Maria Snoussi

Department of Earth Sciences
University Mohamed V
Rabat, Morocco
snoussi@fsr.ac.ma

Dennis P. Swaney

Boyce Thompson Institute
Cornell University
Ithaca, NY, USA
dps1@cornell.edu

James P. M. Syvitski

Environmental Computation and Imaging Group, INSTAAR
University of Colorado, Boulder CO, 80309-0450, USA
Syvitski@Colorado.Edu

R. Kerry Turner

CSERGE, University of East Anglia
Norwich, Norfolk NR4 &TJ, United Kingdom
r.k.turner@uea.ac.uk

William J. Wiebe

Department of Marine Science
University of Georgia
Athens, Georgia 30602, USA
gferreir@com1.med.usf.edu

Eric Wolanski

Australian Institute of Marine Science
P.M.B. No. 3, Townsville M.C. 4810, Australia
e.wolanski@aims.gov.au

Fredrik Wulff

Department of Systems Ecology
University of Stockholm
S-106 91 Stockholm, Sweden
fred@system.ecology.su.se

Wyss W.-S. Yim

Department of Earth Sciences
The University of Hong Kong
Pokfulam Road, Hong Kong SAR, China
wwsyim@hku.hk

Chapter 1

The Coastal Zone – a Domain of Global Interactions

Christopher J. Crossland, Dan Baird, Jean-Paul Ducrotoy, Han Lindeboom
Contributors: *Robert W. Buddemeier, William C. Dennison, Bruce A. Maxwell, Stephen V. Smith, Dennis P. Swaney*

1.1 Introduction

The coastal zone is a zone of transition between the purely terrestrial and purely marine components on Earth's surface. It is widely recognised as being an important element of the biosphere – as a place of diverse natural systems and resources.

Intense interaction characterises the coastal zone. Here, land-dominated global processes and ocean-dominated global processes coalesce and interact, characterised by multiple biogeochemical environmental gradients. The balance of these interactions provides a unique domain of gradient-dependent ecosystems, climate, geomorphology, human habitation and, importantly, regimes of highly dynamic physical, chemical and biological processes.

Coastal processes and natural ecosystems are subject to changes that vary greatly in geographic scale, timing and duration and that combine to create dynamic and biologically productive coastal systems vulnerable to additional pressures resulting from human activities. In turn, the sustainability of human economic and social development is vulnerable to natural and human-induced hazards as a result of our poor understanding of the dynamics of land-ocean interactions, coastal processes and the influence of poorly planned and managed human interventions.

Terrestrial processes are dominated by hydrological regimes and horizontal flows that sustain mechanisms for energy gradients and transfer of materials (nutrients, contaminants, sediments), providing a variety of conditions for material transformations and biological sustenance. Oceanic processes are similarly dominated by hydrological and physical factors that control transport of materials and energy regimes, often in contrast with the land-dominated factors. The resultant balance of terrestrial and oceanic processes yields regional and local heterogeneity in physical and ecological structure, and sustains the dynamics of ecosystem function and biogeochemical cycling in the coastal domain.

The interactions that sustain this balance of processes are in turn influenced by the temporal variability of large-scale phenomena such as CO_2 concentrations in the atmosphere and in seawater and allied temperature changes. Increasingly, humans are influencing these processes and phenomena, resulting in measurable changes directly within the coastal domain and, through feedback, indirectly within the terrestrial, oceanic and atmospheric compartments of the Earth system (Steffen et al. 2004). The result is a diversity of habitats, habitation and areas that are undergoing structural and process changes with significant implications for human society and for the integrity of the coastal zone.

The richness and diversity of resources found in coastal areas have led to a corresponding concentration of human activities and settlement along coasts and estuaries throughout the world. It is estimated that about half of the world's human population lives near the coast and, while the density of coastal populations varies dramatically among regions, there is a general trend of people moving from inland regions to the coast. Clearly the coastal zone will be expected to sustain the livelihoods of a very large proportion of the human population and will remain an important asset to people worldwide, for the foreseeable future.

The coastal zone is also one of the most perturbed areas in the world. Pollution, eutrophication, industrialisation, urban developments, land reclamation, agricultural production, overfishing and exploitation continuously impact on the sustainability of the coastal environment. The major challenge that humans face today is how to manage the use of this area so that future generations can also enjoy its visual, cultural and societal resources. A recent evaluation of the impacts of marine pollution from land-based sources found that marine environmental degradation is continuing and in many places has intensified (GESAMP 2001). The Intergovernmental Panel on Climate Change (IPCC) in 2001 projected increased global atmospheric CO_2 concentrations and temperature elevations that will increasingly, although differentially, influence the coastal zone across regions (Houghton et al. 2001). Global assessment of the environment (OECD 2001), of world resources (WRI 2000, Burke et al. 2001), of oceans and coastal seas (Field et al. 2002), and of global change (Steffen et al. 2002, 2004) describe a tapestry of pressures, impacts and predictions of changes in the coastal zone.

The resources and amenities of the coastal zone are crucial to our societal needs. While it represents about 12% of the world's surface (< 20% of the land surface area and < 9% of the global marine surface area: Costanza et al. 1997), the coastal zone presently is:

- a major food source including major crops and most of the global fisheries,
- a focus of transport and industrial development,
- a source of minerals and geological products including oil and gas,
- a location for most tourism, and
- an important repository of biodiversity and ecosystems that support the function of Earth's systems.

New commercial and socio-economic benefits and opportunities continue to be developed from use of coastal resources, while products and amenities and the issues of environmental management and sustainability challenge planners, managers and policy-makers (Cicin-Sain and Knecht 1998, WRI 2000, von Bodungen and Turner 2001).

A major problem for coastal management is the constant changing of coastal systems, from both "natural" and human causes. Changing wave and current regimes, climate, morphological processes and fluxes of materials from land, atmosphere and oceans are causes of high natural variability, which is still imperfectly understood. Over the last century, humans with their improving technological capabilities have accelerated the rate of change, increasing their influence on the dynamics of already highly variable ecosystems. Our understanding of these impacts, and any decisions for remedial or ameliorating actions, needs to be couched within a wider appreciation of the dynamics of global change, including climate change.

Political, institutional and coastal management initiatives have moved slowly to encapsulate three major conceptual advances embraced by coastal science researchers: (*a*) that humans are an integral component of the ecology and function of ecosystems (for example, von Bodungen and Turner 2001, Smith and Maltby 2003); (*b*) that the water continuum of a river basin catchment (or watershed) and its receiving coastal ocean is a fundamental unit for coastal assessment and management (for example, Salomons et al. 1999); and (*c*) that an ecosystems approach is required for coastal zone management (for example, Wulff et al. 2001).

New tools and techniques have been developed with applications to the coastal zone for scientific inquiry, concept-building, assessment and monitoring (see, for example, Sylvand and Ducrotoy 1998, Sala et al. 2000, UNESCO 2003). These range across observational scales from molecular level assay to measurements from space.

Extended global communications and regional capacity-building have increased public awareness and understanding of coastal zone issues. However, the resolution of problems in the coastal zone remains an enormous challenge if we are to meet the often-stated goals of sustainable resource use and maintenance of Earth system function.

In this chapter, we provide a contextual framework for the coastal zone and its vital interactions, including information about its resources, societal and environmental benefits and values, and an overview of the natural and human pressures and threats that affect the significant changes and dynamics of the global coastal zone. A synopsis is provided of key methodologies and approaches developed and used by LOICZ to assess issues about material fluxes and the interactions between pressures and system responses in this dynamic domain.

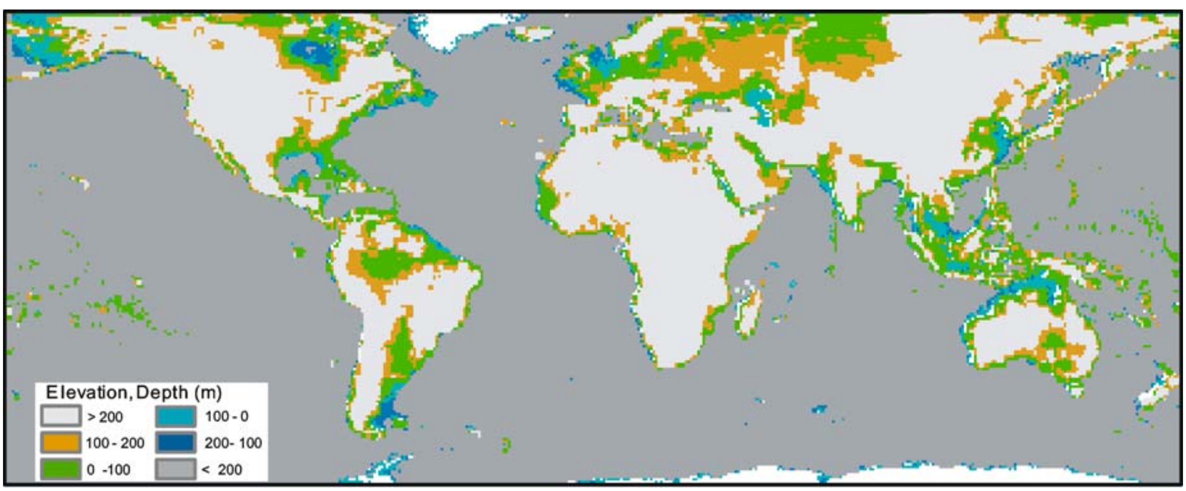


Fig. 1.1. The coastal zone. The LOICZ domain (terrestrial areas: *yellow* 100–200 m elevation, *green* < 100 m elevation; marine areas: *light blue* 100 m depth, *blue* 100–200 m depth)

1.2 What is the Coastal Zone?

The coastal zone comprises a suite of unique ecosystems adapted to high concentrations of energy, sediments and nutrients that stimulate both high biological productivity and a diversity of habitats and species. The variety of ecosystems in the coastal zone encompasses distinctive communities of plants and animals. Powerful and dynamic physical forces continuously shape the coastal zone and its ecosystems and also pose risks to human activities.

The coastal zone (Fig. 1.1) includes river basins and catchments, estuaries and coastal seas and extends to the continental shelf. This relatively narrow transition zone between land and ocean is coupled to phenomena and processes in more distant uplands and offshore waters. Both biogeochemical and socio-economic linkages are included.

There is no single, consistent definition for the coastal zone. Definitions to constrain the spatial boundaries of the coastal zone have ranged from very broad (e.g., extending to the landward and seaward limits of marine and terrestrial influences) to highly restricted (e.g., the coastline and adjacent geomorphological features determined by the action of the sea on the land margin). However, there is now general adoption of the OECD Environment Directorate's approach, wherein the definition of the coastal zone needs to vary according to the type of problem or issue being addressed and the objectives of management (see, for example, Harvey and Caton 2003).

A common rule of thumb is to include the landward area to 100 km from the land-sea interface (WRI 2000, Burke et al. 2001). While this is convenient for generic mapping purposes and captures most of the landward area of the coastal zone, it does not fully embrace vital river catchments and their processes. Recent estimates of coastal population and human exposure to hazards have considered the "near-coastal zone" to include the landward area contained within 100 m elevation of sea level and 100 km of the shoreline (Nicholls and Small

Text Box 1.1. Length of the global coastal zone

Stephen V. Smith

The length of the coastline is dependent upon how it is measured. Mandelbrot (1967) expressed this as a problem in fractals in a classical paper entitled "How long is the coast of Britain?" The answer to the question becomes a matter of both scale and methodology. As long as an internally consistent methodology is used, the question can be answered in an internally consistent and useful fashion. Further, the difference among methods (and scales) can provide information about coastline tortuosity, hence statistical information related to coastal features (e.g., bays, estuaries).

The 2002 CIA World Factbook (*http://www.cia.gov/cia/publications/factbook/*) reports a world coastline length of 356 000 km, based on analysis of a 1 : 35 000 000 map. A summation in the same publication for the coastlines of the world's oceans (at variable scales) gives about 377 000 km, while a summation for the world's countries (with even more variable scales and, probably, variable methodologies) gives a total length of about 842 000 km. Various estimates for the length of the world coastline are provided below, each reasonably well defined.

One approach is based on simple geometry. Consider the coastal zone as a rectangle of known area and width, and calculate the length. The area of the ocean shallower than 200 m is approximately 27×10^6 km^2 and generally the shelf break lies between 110 m and 146 m depth (Sverdrup et al. 1942). This implies that the area to 200 m overestimates the shelf area slightly, so we use a nominal area of 25×10^6 km^2. This is also consistent with estimates derived from the World Vector Shoreline (WVS) ETOPO2 (see below). Hayes (1964) measured the width of the inner continental shelf (< 60 m depth) along 2 136 transects and estimated the average width to be about 17 km. The primary uncertainty in this calculation is that Hayes' transects excluded some areas: much of the Arctic and Antarctic, and also small island shelves. If we assume that the shelf width to ~130 m depth is twice this inner shelf width, then the average shelf width is about 34 km. By this calculation, the estimated length of the coastal zone is $25 \times 10^6/34$, or about 740 000 km. This calculation approximates the world coastline as a long rectangle with a length : width ratio of about 20 000 : 1. The length is about twice the global value reported in the CIA World Factbook and 12% below its country sum.

A second approach is to use a globally consistent high-resolution shoreline available as a GIS layer. The 1 : 250 000 World Vector Shoreline (WVS, *http://rimmer.ngdc.noaa.gov/coast/wvs.html*) has high enough resolution to distinguish most (although not all) of the small lagoonal features. In using equidistant azimuthal projections of the globe (30° latitude zones; polar projections above 60° latitude and geographically centered 30° × 90° boxes at lower latitudes), a coastline length of 1.2×10^6 km is derived. Similar analysis using a 1 : 5 000 000 shoreline (same web-site) gives a length of 600 000 km.

Finally, using gridded data from ETOPO2 (2-minute grid resolution, a length scale varying between about 0 and 3 km, which is latitude-dependent; see Text Box 1.7), yielded a shoreline length of about 1.1×10^6 km.

It is useful to consider these estimates in the context of Mandelbrot's (1967) characteristic length. We assign the WVS a characteristic length (l) of 1 km, based on ability to discern features to about this scale. The 1 : 5 000 000 shoreline is assigned l of 20 times the WVS, or 20 km; the 1 : 35 000 000 is similarly scaled ($l = 140$). The three scales show the following relationship:

$$\text{(coastline length)} = 0.78\, l^{-0.24}$$

From this equation a fractal dimension of 1.24 can be calculated, virtually identical to the value for Britain, which Mandelbrot considered "one of the most irregular in the world." We can then use the regression equation to estimate l for both the ETOPO2 and "simple geometry" cases. ETOPO2 has an apparent l of 1.5, consistent with expectation based on grid spacing; the simple geometry has an apparent l of 7.2 (or a scale of about 1 : 2 000 000). This also seems reasonable.

These calculations are relevant for several reasons. The average width, 34 km, is narrower than the 0.5 degree (~50 km) grid-spacing used in the LOICZ typology. This is a reminder that it is difficult to represent the characteristics of the shelf with even this relatively high resolution grid. Further, for every kilometre of smooth, "simple-geometry" coastline, there are 2 km of coastline irregularities at scales > 1 km. The irregularities include both embayments and promontories.

2002). The seaward boundary of the coastal zone has been subject to a variety of determinants, most of them based on depth bathymetry limits (see also Chap. 3). Reported estimates for the global coastal area and coastline length are also highly variable and the cited metrics depend on the scale and methodology used for the estimation (see Text Box 1.1).

For the purposes of the LOICZ programme, the broad domain of the coastal zone as a global compartment was defined in the LOICZ Science Plan as:

> "extending from the coastal plains to the outer edge of the continental shelves, approximately matching the region that has been alternatively flooded and exposed during the sea level fluctuations of the late Quaternary period" (Holligan and de Boois 1993).

As a general metric, the coastal zone for LOICZ purposes nominally extends from the 200 m land elevation contour seaward to the 200 m depth isopleth (Pernetta and Milliman 1995). This region is viewed as encapsulating most of the material fluxes and processes of transformation, storage and interaction of materials, including human dimensions of the coastal zone. However, operationally in LOICZ and in keeping with the general acceptance of the OECD approach, the setting of the spatial or geographical dimensions of the coastal zone has been determined by the particular issues of land-ocean interaction being addressed.

In the LOICZ Typology approach used to integrate biogeochemical processes and interactions in the global coastal zone (see Sect. 1.5.2 below, and Chap. 3), the coastal domain is described by about 47 000 cells of half-degree resolution, generally extending inland 70–100 km and offshore to the edge of the continental shelf (*http://www.kgs.ukans.edu/Hexacoral*). Assessments of nutrient discharges from land to the coastal sea require consideration of entire catchment (or watershed) areas that often extend beyond the 100 km planar boundary (see Chap. 3). Similarly, the LOICZ assessments of regional and global sediment and water fluxes (see Chap. 2) and of socio-economic inter-relationships with material flows in river basins (see Chap. 4) generally deal with entire river catchments as the vital spatial elements of the coastal zone.

The coastal zone is a relatively small area of Earth's surface. It contains an array of natural ecosystems and habitats, functions as a significant and complex region for biogeochemical transformation, houses more than 45% of the human population and provides wide societal benefits (Table 1.1). Its heterogeneity in physical, chemical, biological and human dimensions and the allied spatial scaling implications ensures that the coastal zone remains a challenge to measure, model and manage.

Biogeochemically, the coastal zone can be considered as a region of dominantly horizontal gradients, exchanges and fluxes. However, vertical flux interactions with atmosphere, soil and groundwater sustain and influence vital processes in Earth's system (Steffen et al. 2004). Temporal dimensions and variability are crucial to the dynamics and natural functioning of the coastal zone. It is not in a steady state, but changes through time in response to different forcings, ranging from daily (e.g., tides and precipitation/river flow) to seasonal (e.g., climatic patterns), annual (e.g., fisheries yield), decadal (e.g., El Niño-Southern Oscillation) and millennial (e.g., sea level was about 100 m lower 8 000 years ago in many parts of the world and considerably higher in Scandinavia than present levels).

A multiplicity of human uses and benefits is derived from the coastal zone (Table 1.2). Resources, products and amenities are as heterogeneously dispersed at local and

Table 1.1. The coastal zone. Global characteristics

The coastal zone:
▪ comprises <20% of the Earth's surface
▪ contains >45% of the human population
▪ is the location of 75% of cities (megacities) with >10 million inhabitants
▪ yields 90% of the global fisheries
▪ produces about 25% of global biological productivity
▪ is the major sink for sediments
▪ is a major site of nutrient-sediment biogeochemical processes
▪ is a heterogeneous domain, dynamic in space and time
▪ has high gradients, high variability, high diversity

Table 1.2. The coastal zone. Resources, products and amenities

Resource – natural materials
▪ Water – surface, ground
▪ Forests and timber
▪ Arable land
▪ Food
▪ Geological ores and deposits
▪ Ecosystems and biodiversity
Products – natural and human derived commodities include
▪ Food
▪ Fisheries
▪ Habitation
▪ Industrial goods and processes
▪ Oil, gas and minerals
Amenities – natural and human-derived services include
▪ Transport and infrastructure
▪ Tourism
▪ Recreation and culture
▪ Biodiversity
▪ Ecosystem services

regional scales as are natural settings and processes, and are subject to changing patterns of availability, quality, limitations and pressures.

The human dimension is crucial in directly and indirectly modifying the entire fabric of the coastal zone through exploitation of living and non-living resources (Vitousek et al. 1997). Urbanisation and land-use changes continue to result in degraded water and soil quality, pollution and contamination, eutrophication, overfishing, alienation of wetlands, habitat destruction and species extinction (Burke et al. 2001). Current research by LOICZ on C-N-P nutrient processes in estuarine systems suggests that there are few, if any, regional examples of unimpacted coastal environments (see Chap. 3).

1.3 System and Human Attributes of the Coastal Zone

Coastal ecosystems are diverse in their living and non-living components; most of them are highly productive, have high degrees of biocomplexity, and provide food and shelter for a myriad of species, including humans. Despite their diversity and structural differences, the ecosystems all have common functional characteristics such as the flow of energy through them and the recycling of the macro- and micro-elements essential for life.

1.3.1 Coastal Ecosystems

The coastal zone contains a number of distinctive biological assemblages including coral reefs, mangroves, saltmarshes and other wetlands, seagrass and seaweed beds, beaches and sand dune habitats, estuarine assemblages and coastal lagoons, forests and grasslands. The ecosystems and habitat assemblages are constrained by their adaptation to a number of dynamic environmental settings: shallow marine environments, marine-freshwater fluctuations and aquatic-terrestrial conditions imposed by the interaction of atmospheric, marine, freshwater and terrestrial elements across the land-ocean boundary (Ibanez and Ducrotoy 2002). These conditions determine a vital mixture of habitats subject to regimes that are too extreme for many purely terrestrial or aquatic plants and animals, including strong salinity gradients, conditions of aquatic emergence-submergence, patterns of hydrological fluctuation and a diversity of energy regimes. Like the flora and fauna, the underpinning biogeochemical cycles and ecological processes of the coastal ecosystems interlink in special ways that are characteristic of both the various ecosystems and the coastal zone itself.

Assessment of the status of coastal ecosystems has been the subject of many efforts and publications, across local to regional scales. However, datasets describing the extent of different coastal habitats remain incomplete and often inconsistent (see Burke et al. 2001). Generally, the data encompass only local areas, so that a limited patchwork of information is available at local and sometimes regional scales (Sheppard 2002). Historical records are rarely available and, when present, the reliability of data and geo-referencing is often questionable. These limitations are being addressed by an increasing number of nations, as efforts are being made to assess national resources, to meet legislative requirements for state of environment reporting, and in the course of academic and applied management studies (e.g., in Australia, Wakenfeld et al. 1998, SOER 2002; in North America, UNEP 2002).

At a global scale, a recent report on world resources 2000–2001 (WRI 2000) provided a score-card that painted a less than desirable picture of the state of the global coastal zone. The Intergovernmental Oceanographic Commission (IOC) program of coral reef assessment considered that human activities continue to threaten their stability and existence, with 11% of global reefs lost and 16% not fully functional (Wilkinson 2000). Regional differences in the level of impacts on coral reefs are exemplified by the Southeast Asian region where 86% of reefs are under medium to high anthropogenic threat, particularly from over-fishing, coastal development and sedimentation (Talaue-McManus 2002).

Globally, mangroves are considered to have been reduced by more than half (Kelleher 1995); in Southeast Asia more than two-thirds of mangrove forests have been destroyed since the early 1900s, with current loss rates ranging between 1–4% per year (McManus et al. 2000). While some re-forestation of mangroves is occurring (by planting at local scales and as a result of changes in sedimentation processes), the net global trend in areal distribution and ecosystem quality is downwards (Burke et al. 2001). Direct loss of other wetlands and seagrass meadows near the coastal interface has been documented at regional and local scales but a comprehensive global assessment has yet to be achieved. In all cases, the changes in the extent of coastal habitats around the world result from a mosaic of local and regional differences in the intensity of societal and climatic pressures (see Fig. 1.3) operating across various spatial and temporal scales.

The diverse chemical, physical and biological processes integrated within habitats or coastal ecosystems are crucial in providing socio-economic goods and services for humankind (Costanza et al. 1997, also see Sect. 1.4.3). Scientifically, our understanding of the key processes dominating in any specified ecosystem has improved greatly over the last few decades. Concepts and methods for studying integrated processes within coastal ecosystems continue to be developed and extended (e.g., Alongi 1999, Black and Shimmield 2003, Lakhan 2003). Similarly, there have been advances in our understanding of the integrated processes and regimes of feedbacks between the fluxes of physical, chemical and biological materials between ecosystems; for example, between UK rivers and the North Sea, by the Land Ocean Interaction Study (LOIS: Neal et al. 1998, Huntley et al. 2001) and between the Great Barrier Reef and adjacent land catchments (Wolanski 2001).

However, we are still grappling with ways to measure and assess changes in coastal ecosystem processes across spatial scales to allow an understanding of regional and global changes in the functioning of coastal ecosystems.

A recent expert workshop (Buddemeier et al. 2002) addressing disturbed and undisturbed nutrient systems in estuaries and coastal seas examined a number of typological databases of the global coastal zone in an effort to partition different variables influencing coastal systems: the biophysical (indicative of the system dynamics) and the anthropogenic (indicative of a strong river-basin influence). Because sea temperature is known to play a major role in structuring ecological patterns in the ocean, influencing the distribution of ecosystems (coral reefs, salt-marshes and mangroves, seagrasses and kelp beds) and indicating sites of major coastal upwelling, the globe was partitioned on the basis of sea-surface temperature into polar (< 4 °C), temperate (4–24 °C) and tropical (> 24 °C) zones to represent major coastal climatic regions (Fig. 1.2). Increasing evidence suggests that anthropogenic influences in small to medium catchments may have a much greater influence on the changes in material flows to the immediate coastal seas than large catchment (see Chapters 2 and 3).

Further expert judgement yielded separate concept diagrams for the processes and conditions affecting biogeochemical fluxes in each coastal region (Fig. 1.3). These diagrams demonstrate clear latitudinal differences in the dominant material fluxes, as well as the key processes and their susceptibilities for change in each climatic region. Further, the expert workshop considered that the major phenomena and processes impacting on coastal ecosystems differed among regions, viz., soil erosion in tropical regions, eutrophication (*sensu* Richardson and Jørgensen 1996) in temperate regions, climate change in polar regions. At a global scale, direct alteration of coastal ecosystems was considered the major factor forcing change (e.g., altered hydrological conditions, altered landscape, sea-level rise).

1.3.2 Variability in Coastal Ecosystems

Environmental conditions in coastal ecosystems are not constant. They vary seasonally and annually, and such changes are difficult to predict through time. On a geographical scale, coastal ecosystems differ greatly in size, from a small estuary to a fjord or a bay. Estuaries themselves differ by orders of magnitude, yet they all have common properties and processes (see Chap. 3). The same system may vary in a number of ways (e.g., rates of production, diversity) on seasonal or decadal scales.

Changing wave and current regimes, climate, geomorphological processes and fluxes of chemicals and nutrients from land, atmosphere and ocean result in a highly variable environment in which interactions are still imperfectly understood. In recent years humans have accelerated the rate of change (Lindeboom 2002b, in press). Impacts originate locally and regionally, but influence globally, so that the climate of the planet is changing dramatically (Tyson et al. 2001, Steffen et al. 2004).

1.3.2.1 *Temporal and Spatial Scales of Variability*

Coastal marine ecosystems undergo continuous changes in rates of production, species abundance and community composition. A holistic understanding of the full effects of human impacts on natural process variability is still lacking (Lindeboom 2002b).

Long-term datasets on phytoplankton, zooplankton, macrofauna, fish and birds have been collected around the world, and have been used to demonstrate the effects of anthropogenic impacts on ecosystems. These datasets show that fluctuations in abundance or in productivity are in some cases very sudden and unpredictable, not

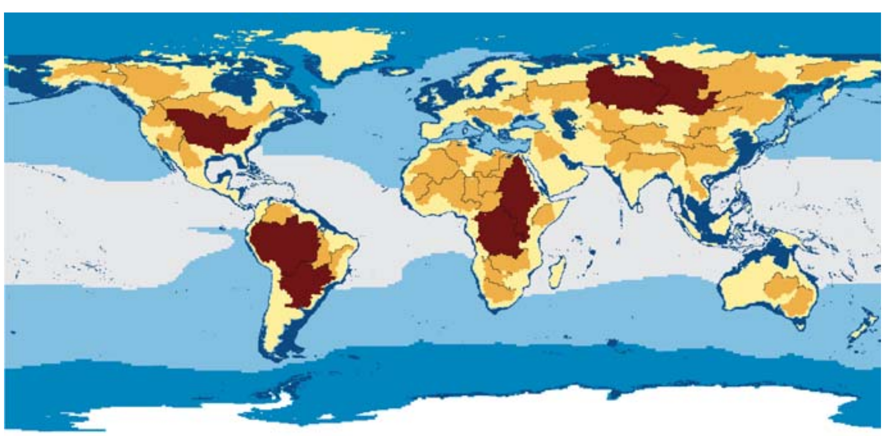


Fig. 1.2.
The coastal zone. Latitudinal relationships between the broad coastal domain (landward from the 200 m isobath, *dark blue*) and polar (< 4 °C, *light blue*), temperate (4–24 °C, *pale blue*) and tropical (> 24 °C, *grey*) regions defined by sea surface temperature. The *brown and orange areas* are major river basins; the *yellow zone* merges the small and medium-small river basins (< 5 × 10^5 km^2) that dominate the coastal zone (see Chap. 3; modified from Buddemeier et al. 2002)

10^5

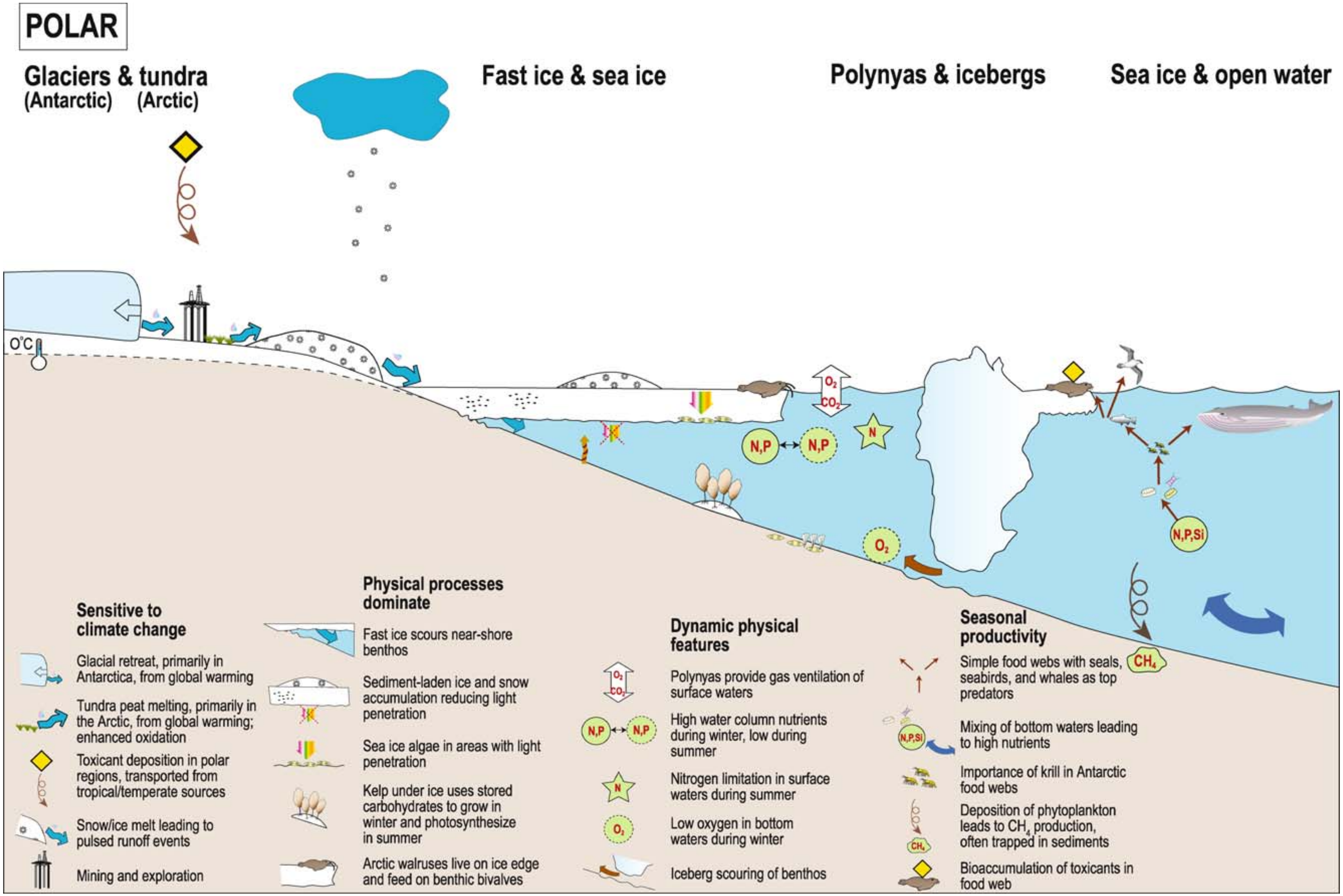


Fig. 1.3a. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in polar coastal zones

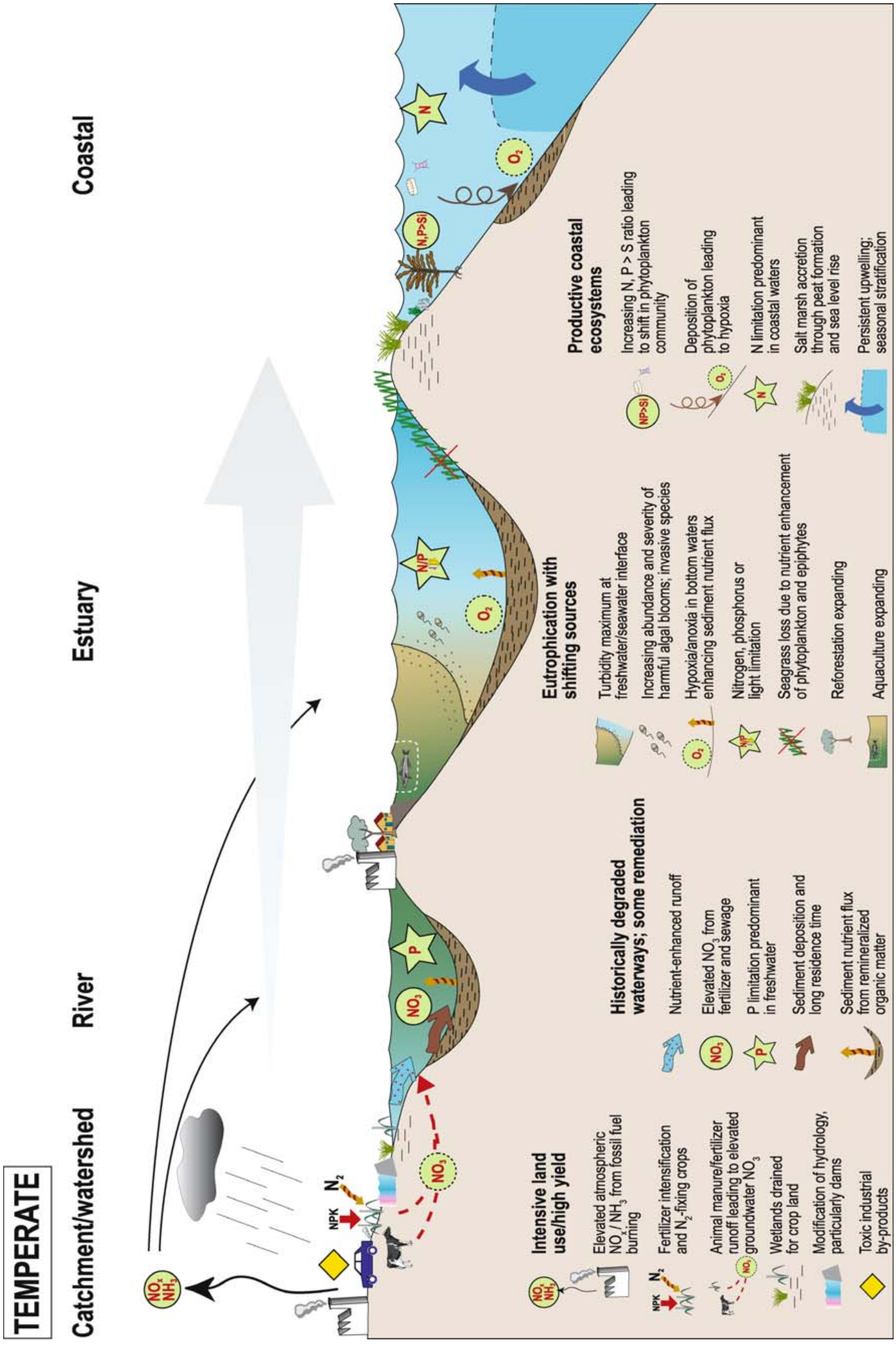


Fig. 1.3b. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in temperate coastal zones

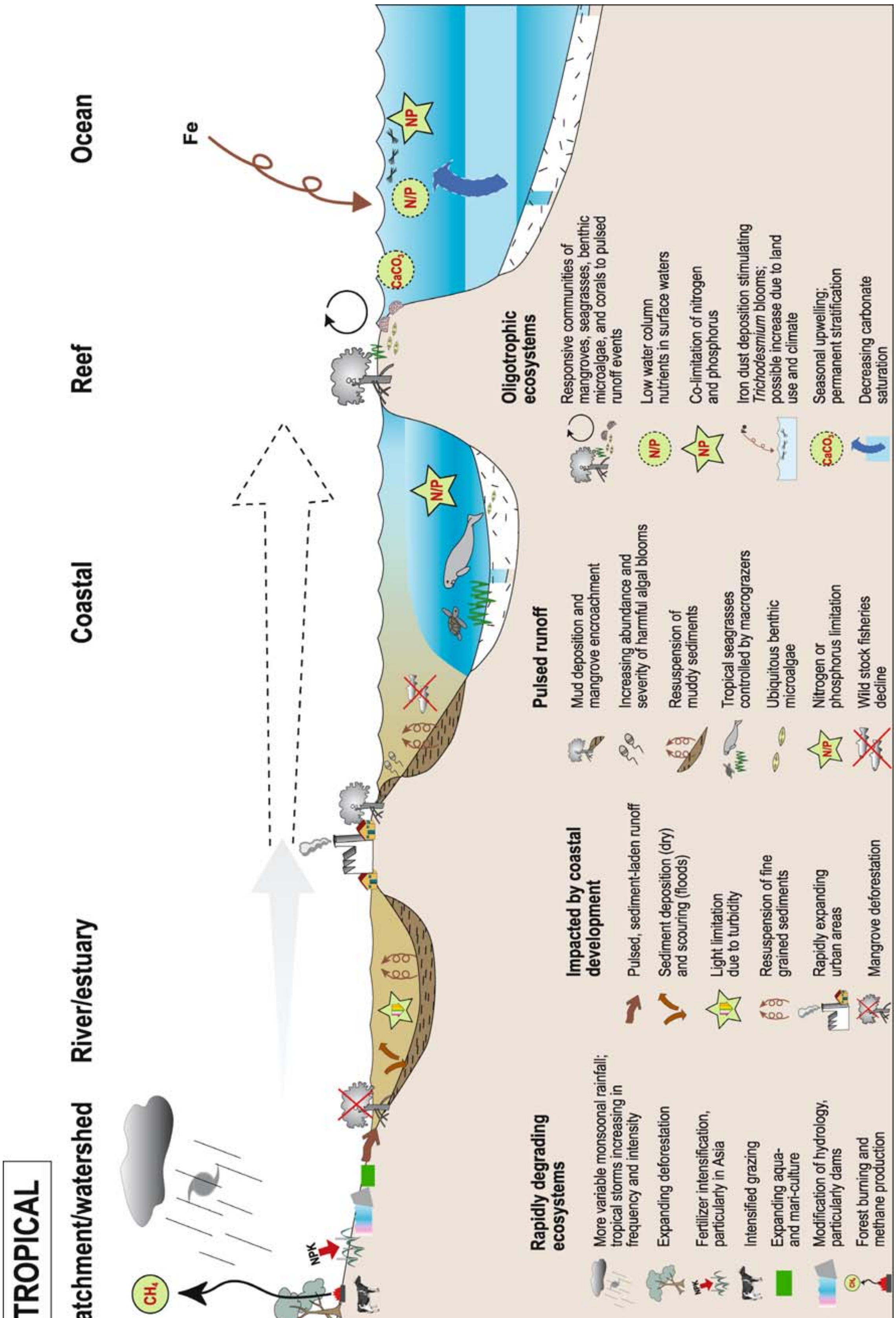


Fig. 1.3c. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in tropical coastal zones

gradual if due to a steady increase in human impacts (Lindeboom 2002a). Variability in ecosystem processes and in their biotic components can also vary dramatically over spatial scales. For example, at a global level, the El Niño-Southern Oscillation (ENSO) cycle in the Pacific basin is known to result in the almost complete failure of fisheries in South American waters and in many other ecological deviations worldwide every 4–7 years. Similarly, the North Atlantic Oscillation (NAO), a response to periodic changes in atmospheric pressure differences in the North Atlantic, has increased in the past few decades, causing changes in water and air circulation and influencing the distribution and diversity of key zooplankton that support coastal and regional fisheries (Text Box 1.2).

Spatial variability in ecosystem behaviour is determined to a large degree by biological dynamics, or the scales over which individual components interact, and by internal and external forcing functions. Recent work on the measurement of material and energy flows among ecosystem components has shown that the efficiency with which energy is transferred, assimilated and dissipated not only influences the fundamental structure and function of the system as a whole, but also causes differences and similarities in the way systems operate.

Comparative studies among systems which differ in size and shape over spatial scales have made use of network analysis and ECOPATH modelling approaches, from which common system properties such as the magnitude of recycling, ascendancy, development capacity and flow diversity can be derived (Wulff et al. 1989, Baird and Ulanowicz 1989). These studies showed that the magnitude of C, N and P recycling is higher in detritus-based systems such as estuaries, compared with plankton-dominated upwelling systems. The structure of recycling is relatively simple (i.e., short cycles) in chemically-stressed systems compared with those more "pristine" systems where longer cycles and more complex cycle structures prevail. Further, the ratio between the development capacity and ascendancy is higher in less disturbed (e.g., upwelling systems) than in eutrophied or chemically-impacted systems (for example, Baird 1998, 1999; Baird et al. 1991, 1998; Baird and Ulanowicz 1993, Christensen 1995, Christian et al. 1996). These analytical methodologies are most useful in the assessment of ecosystem function by comparing system properties. However, the required quantitative data describing standing stocks and flows between the components are not available for many coastal ecosystems (Baird 1998).

Seuront et al. (2002) studied ecosystem patterns arising in relation to prevailing local conditions. They showed that nutrient patches in tidally-mixed coastal waters in the eastern English Channel are caused by its megatidal regime and the resultant high turbulence. While purely passive factors, such as temperature and salinity, are generally regarded as being homogenised by turbulent fluid motions, recent studies have demonstrated that these parameters are also heterogeneously distributed at smaller scales than predicted; associated delimiting fronts or boundaries between different water patches are characterised by high phytoplankton production and high numbers of associated zooplankton (Mann and Lazier 1996). Links have been suggested with changes of short-term or large-scale weather patterns, wind, winter and/or summer temperatures or rainfall (Lindeboom 2002a), emphasising the interaction between local and global influences.

Temporal variability in coastal ecosystem properties and rates is well documented. In the long term, a shift in storm frequencies or wind directions may cause changes in the mixing of water masses and the deposition of sediments (Lindeboom 2002a). In temperate regions the occurrence of cold winters strongly influences the species composition of intertidal benthic communities (Beukema et al. 1996, Ibanez and Ducrotoy 2002). Possible causes of these observed phenomena include changes in water or nutrient fluxes from the land or sea, and internal processes in the marine ecosystem.

Different impacts can yield similar effects in ecosystems, while local human disturbances often further complicate the analyses. A substantial body of literature exists on changes in ecosystem properties across temporal scales. The studies reported clearly illustrate the dynamic and variable nature of ecosystem processes over time; for example, Warwick (1989) on seasonal changes in estuarine benthic communities, Gaedke and Straile (1994) on seasonal changes and trophic transfer efficiencies in planktonic food webs, Field et al. (1989) on the successional development of planktonic communities during upwelling, Baird and Ulanowicz (1989) on the seasonal dynamics of carbon and nitrogen, Fores and Christian (1993) and Christian et al. (1996) on nitrogen cycling in coastal ecosystems, Baird and Heymans (1996) on changes in system properties of an estuary over decades due to reduced freshwater inflows, Baird et al. (1998) on spatial and temporal variability in ecosystem attributes of seagrass beds, and Rabelais et al. (1996, 2002) on a river-influenced coastal system response to changing nutrient loads (see Text Box 5.1, Chap. 5).

There is growing evidence that the cycles long recognised in freshwater systems and trees occur in marine sediments (Pike and Kemp 1997), corals (Barnes and Taylor 2001), shellfish (Witbaard 1996) and coastal marine systems (Bergman and Lindeboom 1999). However, despite an increasing number of examples for many types of biota around the world, cyclical behaviour (e.g., in numbers of organisms in coastal seas) remains disputed. Until lasting and predictable cycles with clear cause-ef-

Text Box 1.2. North Atlantic Oscillation influences copepod abundance and distribution

Jean-Paul Ducrotoy

The North Atlantic Oscillation (NAO) is defined as the pressure difference between the Icelandic Low and the Azores High (Fig. TB1.2.1). It determines the strength of the prevailing westerlies and other wind patterns in the North Atlantic which in turn affects the ocean surface currents there and the movement of water towards north-western Europe, in particular into the North Sea.

The influence of this phenomenon on the physical and biological functioning of the North Sea requires further study (Ducrotoy et al. 2000), but it is predicted that the flows of the North Atlantic Current and the Continental Slope Current along the European Shelf Break, which determine the rate of heat transfer towards Europe, have a large influence on biodiversity. Present-day patterns in pelagic biodiversity are the result of the interaction of many factors acting at different scales. Temperature, hydrodynamics, stratification and seasonal variability of the environment are likely to be main factors contributing to the ecological regulation of the diversity of planktonic organisms.

The similar geographical patterns evident between currents/water masses and species associations suggest that the species groups may be used as environmental indicators to evaluate long-term changes in the marine environment related to climate change and other increasing human-induced influences (Beaugrand et al. 2002).

Changes are visible in biologically distinct areas of seawater and coasts, recognised by scientists as large marine ecosystems. Geographical changes in the diversity of planktonic calanoid copepods have been studied in the North Atlantic and the North Sea based on historic data collected by Continuous Plankton Recorder (CPR) surveys (Warner and Hays 1994). Detectable year-to-year or decadal changes in the diversity of pelagic communities of this region may be expected to have already occurred, or may change in the future due to climate change. Over the last decade there has been an increase in the abundance of a number of arctic-boreal plankton species (Fig. TB1.2.2), notably *Calanus hyperboreus, Calanus glacialis* and *Ceratium arcticum*, and a southerly shift of the copepods *C. hyperboreus* and *C. heligolandicus* in these areas.

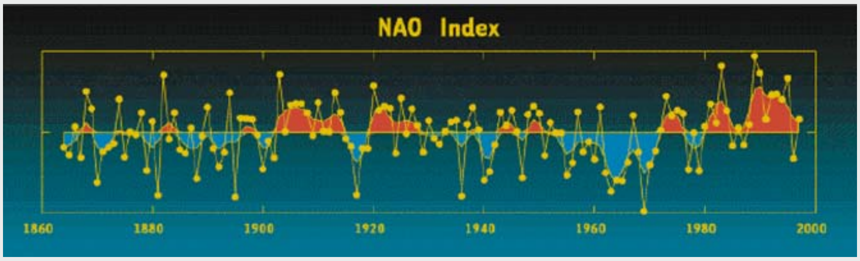


Fig. TB1.2.1. The anomalous difference between the polar low and the subtropical high during the winter season (December-March) measured using NAO index variations

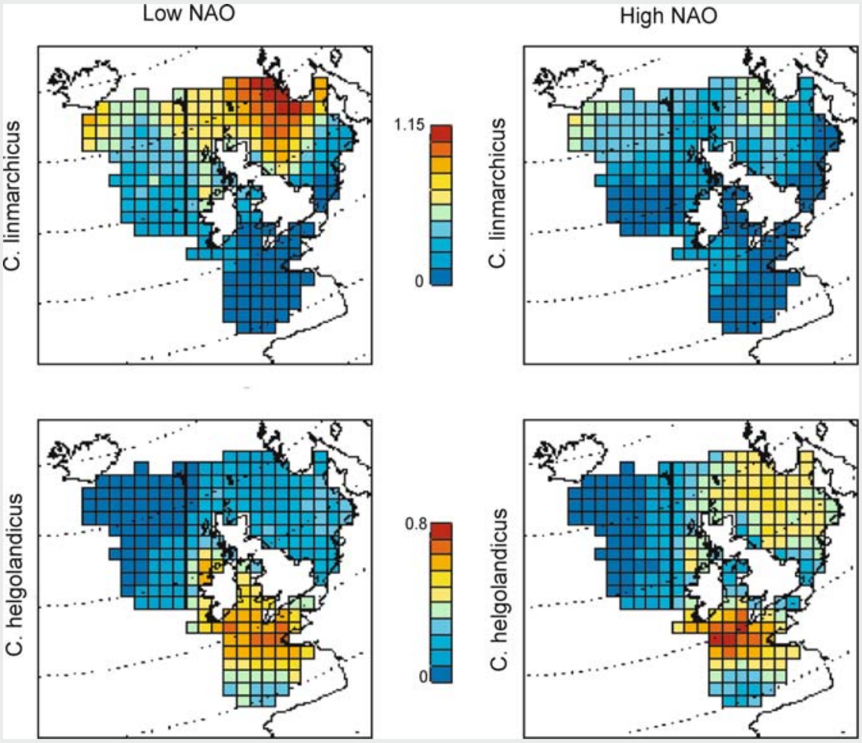


Fig. TB1.2.2. Distribution of copepods (*Calanus helgolandicus*, *C. linmarchicus*) and NAO state, 1986–1996 (from Reid et al. 1998) fect relationships are proven, it remains questionable whether this is really the result of complex physical-biological interactions or just a coincidental, statistical feature of datasets. The number of papers suggesting links between observed cyclical events and solar activity is increasing. Very long datasets also indicate alternations of cyclical periods with periods without cyclical patterns (Lindeboom 2002a). Long-term data-series, in combination with the results of experimental laboratory and field studies, are necessary to provide insights and understanding of trends in coastal ecosystems and whether they are due to local-scale disturbances and/or to global climatic changes.

1.3.2.2 *Climate Change and Variability*

Earth's climate is subject to natural cycles (Petit et al. 1999, Rial 2004, Steffen et al. 2004). Cycles may occur over short time-scales or may span decades, centuries or millennia, so that change rather than stability characterises the global system and subsequently the coastal environment.

Climate change is not climate variability. Scientists have struggled to gain an understanding of coastal ecosystem responses to seasonal, inter-annual and, to a degree, decadal time scales, but prediction of responses to climate change opens up new and larger challenges. As Busalacchi (2002) stated: "*Detection of climate change is the process of demonstrating that an observed variation in climate is highly unusual in a statistical sense. Detection of climate change requires demonstrating that the observed change is larger than would be expected to occur by natural internal fluctuations.*"

There is a large weight of evidence that Earth systems are now subject to a regime of significant climate change, driven especially by a continuing increase in atmospheric CO_2 concentrations in response to anthropogenic actions (Fig. 1.4; Houghton et al. 2001, Steffen et al. 2002, Walther et al. 2002). Direct CO_2 effects and allied temperature increases have a number of ramifications for the functioning of the Earth systems including the ecosystems of the coastal zone (Steffen et al. 2004).

The rate and duration of warming in the 20th century was greater than in any of the previous centuries – and humans are modifying the rate of change (Moore 2002). The global average surface temperature has increased by 0.6 °C since 1900 and, from modelling projections, is expected to increase by about 2.5 °C (1.5 to 4.5 °C modelled range) over the next 100 years. Such climate changes are a response mainly to increases in "greenhouse gases" and are part of a global change affecting Earth's energy balance, which in turn influences the atmospheric and oceanic circulation patterns and, hence, weather systems. However, there are large regional variations in the spatial manifestation of these temperature patterns, including cooling in some areas.

Changes in response to natural or anthropogenic forcing have the potential to push ecological systems beyond

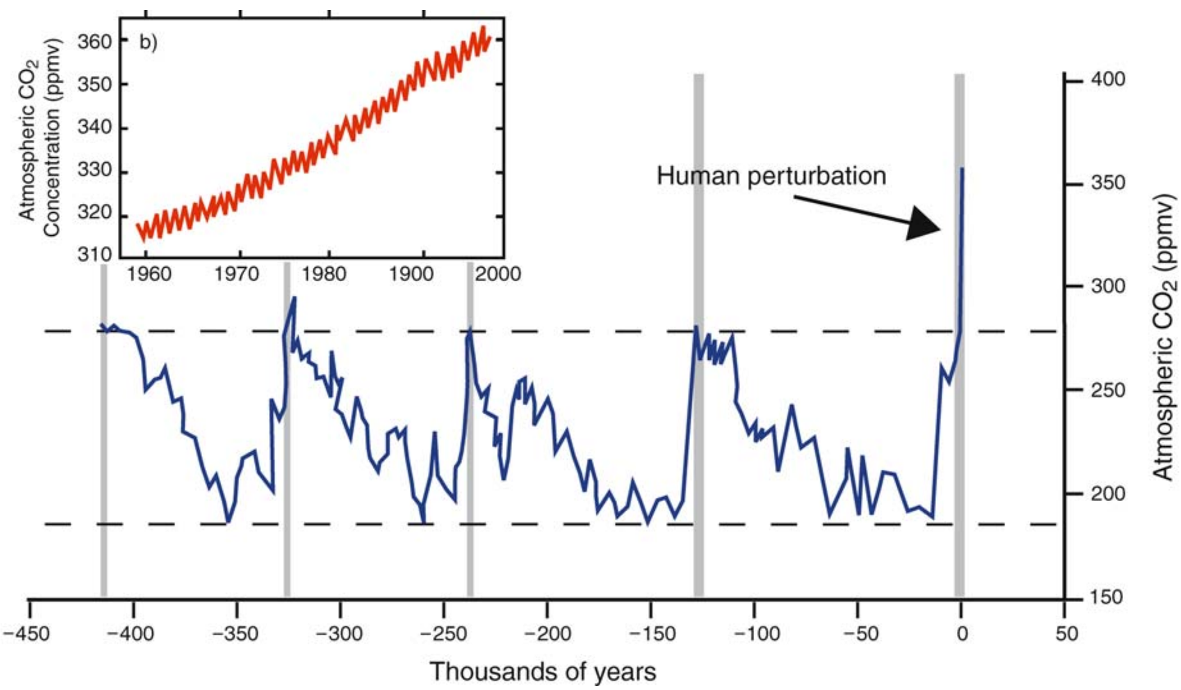


Fig. 1.4. The coastal zone. Atmospheric CO_2 concentration from the Vostok ice core data, with human perturbations superimposed (from Steffen et al. 2002, derived from Petit et al. 1999 and NOAA)

their limits of sustainability and to increase variability in environmental conditions. For example, calcification rates in coral reef systems continue to decline in response to increasing levels of atmospheric CO_2 (see Text Box 3.2, Chap. 3), and elevated sea-surface temperatures are firmly associated with widespread coral bleaching events (Hughes et al. 2003, Buddemeier et al. 2004). Changes in temperature and precipitation patterns already affect runoff and flow in rivers. In Southeast Asia, low-lying areas are experiencing an increased frequency of typhoons and flooding, while monsoonal shifts are influencing patterns of sedimentation and nutrient delivery from the land; these can lead to changes in coastal ecosystem structure and function (Talaue-McManus 2002).

The physical responses of estuaries and coasts to sea-level rise at local scales will depend on a combination of eustatic movements (reflecting the increase of seawater in the oceans) and isostatic movements (due to the tilting of land masses in relation to the melting of the ice cap; also see Sect. 2.2, Chap. 2.2). Estimates of the magnitude of the sea-level rise have been based on a doubling of atmospheric CO_2 resulting in an overall sea-level rise of about 48 cm by 2100, which is 2–4 times the rate observed through the 20th century (Houghton et al. 2001).

Along the open coast, an increase in wave occurrence linked to an increase in high-tide level will lead to widespread erosion with a landward migration of the high-tide mark and a flattening of the shore slope. In the Atlantic Ocean, wave heights have increased by 2–3 cm per year over the last 30 years (von Storch and Rheinhardt 1996). If the shore is protected by embankments, the intertidal profile will probably steepen, with a concomitant reduction in the areas occupied by intertidal communities. Associated with such sea-level rise, estuaries will simply become "arms of the sea", with dramatic impacts on their unique biodiversity, system function and habitats (Ducrotoy 1999). Possible consequences of climate change on the biology of coasts and estuaries include a shift of high-energy habitats towards the outer parts of the coast and a change in the rates of biogeochemical cycles.

The possible effects of predicted climate changes need to be considered (for example, Walther et al. 2002). The direct effects of increased CO_2 on living organisms will have a bearing on carbon fixation pathways, in particular photosynthesis. An increase in primary production could be expected but a change in cloud albedo may have a negative effect on the metabolism of plankton. A decrease in seawater pH could lead to shell dissolution in molluscs and corals, while a lack of availability of essential metal ions would have a negative effect on the growth and morphology of coastal organisms. Recent experiments have shown certain algal species (in particular the red algae, Phylum Rhodophyta) to be sensitive to changes in temperature, length of photoperiod and solar radiation intensity (see for example, Molenaar and Breeman 1997).

Variability of ecosystems is a major feature of all domains and knowledge of the fundamental mechanisms and their response to local climates is essential for the establishment of appropriate management strategies for the coastal zone. Variability of coastal systems depends on two major forcing factors: the climate/meteorology and, directly or indirectly, anthropogenic activities. Both factors have an impact on the ecology and physical structure of the coastal environment and on its dynamics and biogeochemistry, thus influencing the biological performance of the coastal systems. The structure and organisation of communities, conditioned in each coastal environment by a combination of abiotic factors, also depend upon biological characteristics such as recruitment and productivity rates. Keystone species may control local biodiversity through indirect effects, disproportionately larger than their relative abundance, and hence have an impact on the local natural variability, notably by changing local habitats (Piraino et al. 2002) and the biogeochemical cycles involved in their maintenance (Ducrotoy et al. 2000).

Historically, humans have been closely associated with the coast, in part reflecting the evolution of trade and commerce and access to resources. The industrial revolution led to marked increases in coastal transport and population impacts such as human and industrial waste discharge and food extraction. In recent times, the growing popularity of recreation and leisure pursuits is significantly increasing direct human activities.

The impact and influence of humans in the coastal zone is widely recognised locally and is increasingly apparent across most regional scales (Fig. 1.5). However, information about human (or anthropogenic) impacts is poorly described at global scales. Even reported estimates for population numbers and densities are quite disparate. Much depends on:

a the source and quality of the population database (usually derived by modelling of census data from global administrative units which often have different census dates and resolution),
b the year to which the modelled population date is standardised, and
c the definition and methodology used to determine the spatial units and dimensions that encapsulate the coastal zone (Shi and Singh 2003).

Recent estimates of population in the coastal zone range from 23% (Nicholls and Small 2002) to about 50% (Watson et al. 1997). Burke et al. (2001) cited estimates based on CIESIN 2000 data derived from census of administrative units that yielded values of 2.075×10^9 people in 1990 and 2.213×10^9 people in 1995 (39% of global

Fig. 1.5. Night light image of Earth (NASA, *http://www.gsfc.nasa.gov*)

population) living within 100 km of the coast. Using the relatively robust dataset for 1990 contained in the Gridded Population of the World Version 2 (CIESIN 2000 data; *http://sedac.ciesin.org/plue/gpw*), and an elevation model (*http://www.edcdaac.cr.usgs.gov/landdaac*), Nichols and Small (2002) estimated that 1.2×10^9 people (23% of global population) live in the "near coastal zone" (the coastal area within 100 m elevation and 100 km of the coast).

The LOICZ typology database (*http://www.kgs.ukans.edu/Hexacoral/Environdata/envirodata.html*), using gridded population data for the coastal domain derived from LandScan for 1998 (*http://www.ornl.gov/sci/gist/landscan*), yielded an estimated 2.69×10^9 people (44% of global population) within the coastal zone. For this technique, the coastal zone is contained within a grid of half-degree cells, representing a linear measurement at the equator of 100 km landward of the coastline (see Text Box 1.7). These estimates are still lower than the generalised value of $> 3 \times 10^9$ people often broadly ascribed to the coastal zone by various authors through the mid 1990s (e.g., Hinrichsen 1998). Improved data collection and application of consistent methodologies would provide robust estimates of the current coastal population for application to trend analyses, modelling and prediction of human pressures and changes in the coastal zone.

The coastal population is increasing disproportionately to the global population increase. In their analyses, Shi and Singh (2003) estimated an average population density for the coastal zone (within 100 km from the coastline) of 87 people km^{-2} in 2000 compared with 77 people km^{-2} in 1990 (UNEP/GRID database, *http://www.na.unep.net*). The average global population in 1990 was 44 people km^{-2}. Elevated population densities coincide with urban conurbations and "altered" landscapes (Burke et al. 2001). In 2000, 17 of the world's 24 megacities were coastal (Klein et al. 2003). There is a marked diminution of population density with distance from the coast, with 40% of the "near coastal" population occupying only 4% of the land area at densities > 1 000 people km^{-2}, with greatest densities in Europe and in South, Southeast and East Asia (Nicholls and Small 2002). Illustrated in Fig. 1.5, this highlights the additional observation by Nicholls and Small that "*… despite the concentration of people near coasts, at the global scale, the majority of land area within the 'near coastal zone' is relatively sparsely populated*". This coastal density imbalance is likely to increase with time

Table 1.3. The coastal zone. Estimated and projected average population density for the coastal zone and inland areas (derived from Shi and Singh 2003) and projected global population estimates (UN/DESA 2001–03)

Date	Average population density (people km^{-2})		Estimated global population (billion)
	Coastal Zone	Inland	
1990	77		5.2
2000	87	23	6.1
2010	99	38	6.9
2025	115	44	7.9
2050	134	52	9.3

Table 1.4.
The coastal zone. Natural and anthropogenic forcings and associated phenomena of interest in coastal marine ecosystems (adapted from UNESCO 2003)

	Forces
Natural	▪ Global warming and sea level change ▪ Storms and other extreme weather events ▪ Seismic events ▪ Ocean currents , waves, tides and storm surges ▪ River and ground water discharges
Anthropogenic	▪ Physical restructuring of the environment ▪ Alteration of the hydrological cycle ▪ Harvesting living and nonliving resources ▪ Alteration of nutrient cycles ▪ Sediment inputs ▪ Chemical contamination ▪ Inputs of human pathogens ▪ Introductions of non-native species
	Phenomena of interest
Marine services, Natural hazards and Public safety	▪ Increasing in sea level ▪ Changes in sea state ▪ Changes in surface currents ▪ Coastal flooding events ▪ Changes in shoreline and shallow water bathymetry
Public health	▪ Seafood contamination ▪ Increasing abundance of pathogens (in water, shellfish)
Ecosystem health	▪ Habitat modification and loss ▪ Changes in biodiversity ▪ Eutrophication ▪ Water clarity ▪ Harmful algal bloom events ▪ Invasive (non-indigenous) species ▪ Biological affects of chemical contaminants ▪ Disease and mass mortalities of marine organisms ▪ Chemical contamination of the environment
Living resources	▪ Abundance of exploitable living marine resources ▪ Harvest of capture fisheries ▪ Aquaculture harvest

(Table 1.3). The coastal zone now contains more than 45% of the global population, within < 10% of the global land area. The projected global increases in population will occur mostly in developing countries (Burke et al. 2001).

Some of the migration towards the coast is temporary, although it can be significant during certain periods (Cook 1996). Patterns of tourism and global trade exacerbate coastal population densities, locally and regionally. For example, the Mediterranean coastal zone population swells from 130 million to 265 million for most of each summer, increasing transportation and pollution problems, and the number of visitors is expected to rise to 353 million by 2025 (Salomons 2004).

Thus, population pressure in the coastal zone poses major challenges for coastal management and planning agencies. This is complicated because human pressures are highly variable in type and intensity at local levels and are often connected across wide geographical distances by global tourism, transportation and trade patterns. It is now considered that "*… human activities are influencing or even dominating many aspects of the Earth's environment and functioning …*" leading to the suggestion that we are now in "*… another geological epoch, the* ***Anthropocene*** *era*" (Steffen et al. 2002).

1.4 Changes to the Coastal Zone

Numerous natural and human-induced forces influence coastal ecosystems. These forces have direct and indirect effects on coastal ecosystems, modifying various aspects of societal interest, including marine services, natural hazards and public safety, public health, ecosystem health and living resources. Each of these is affected or impacted by one or more phenomena, as shown in Table 1.4. The distinction between natural and anthropogenic forcings is somewhat artificial. Although some forcings are clearly of human origin (e.g., harvesting of marine resources, chemical contamination), there are few if any natural phenomena that do not now have a human signature of some sort (e.g., climate change, river and groundwater discharges, nutrient enrichment) (UNESCO 2003).

Coastal ecosystems are diverse but inter-related through common functional processes and subject to the same natural and anthropogenic impacts. The response of different systems to one or more phenomena may not be the same, because some are more resilient than others. However, management of coastal ecosystems requires an integrated, holistic philosophy and practice as opposed to a piecemeal approach (Allanson and Baird 1999).

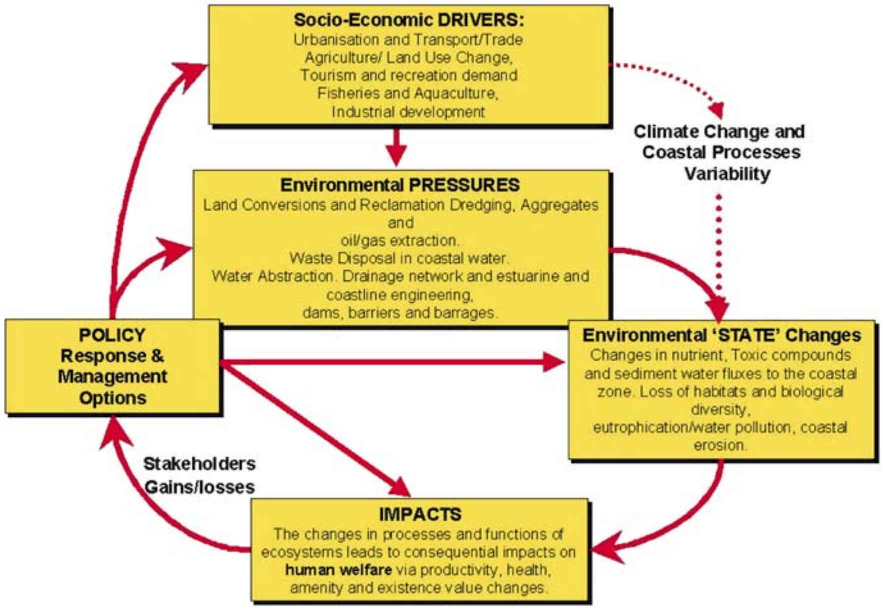


Fig. 1.6.
The coastal zone. Schema of DPSIR framework (adapted from Turner et al. 1998)

Research and environmental management approaches during the last decade have markedly improved our knowledge of how global environmental change and human activities influence the coastal zone – its ecology, function, products and benefits. We know there is continuing degradation of ecosystems, their benefits and resources. We know there are opportunities for wiser use of the coastal zone and that there is a need for greater preparedness to meet changes in the coastal zone. However, we are limited in our ability to scientifically and objectively measure, assess and predict the natural and human dimensions of these changes and the effects of different pressures on ecosystems.

Differentiating human-induced changes from naturally-forced changes remains a challenge. These problems derive from the complexity of endogenous natural functions and biogeochemical interactions, the inherent complexity and scales of the human dimension and the synergies, feedbacks and disconnects in the scale of linkages and relationships between natural ecosystems and socio-economic interactions in the heterogeneous landscape of the coastal zone. However, targeted research and new tools for measurement and conceptualisation are delivering exciting and often surprising outcomes (see, for example, Steffen et al. 2002, 2004). While the intellectual challenges in this work are high for people involved in the science, management and policy arenas, an equally important challenge is to find ways to effectively communicate and apply the knowledge across the wider global community as well as to specific users of the information (Ducrotoy and Elliot 1997, Crossland 2000, Olsen 2003).

LOICZ has adapted and used the Driver-Pressure-State-Impact-Response (DPSIR) framework (Fig. 1.6; Turner et al. 1998, Turner and Salomons 1999) to organise commentary and research approaches (see Sect. 1.5.3) on the dominant forcings (Pressures) and effects (Impacts) on the global coastal zone (Table 1.5). The Drivers and Pressures on coastal systems are predominantly the result of societal function and human behaviour and may be amenable to management and policy decisions (Response). It is increasingly apparent that forcings on coastal ecosystems by most natural Drivers and Pressures are greatly modified by human activities in both extent and intensity.

The natural dynamics of Earth's interlinked geophysical systems provide stressors that result in structural, ecological and biogeochemical changes to all regions of the globe. Human activities greatly exacerbate many of these changes. Recent assessments by the global research alliance IGBP-IHDP-WRCP-DIVERSITAS concluded: "*… we know that the Earth System has moved well outside the range of natural variability exhibited over the last half million years at least*" (Steffen et al. 2004).

The magnitudes and rates of changes now occurring in the global environment are unprecedented in human history, and probably in the history of the planet. Earth is now operating in a "*no-analogue state*" (Steffen et al. 2002). The system changes and changed forcings or stressors act as Pressures and Drivers on the state and function of natural systems and processes within the coastal zone. The global coastal zone has been highly dynamic through geological time in response to natural forcing. The actions of human society are drastically impacting on the structures, resources and processes of the coastal zone. Human pressures and forcings will increase, with probable unforeseen ramifications for global society.

Table 1.5. The coastal zone. Systems and their key pressures (from GESAMP 2001)

System	Key pressures
Coral reefs	Eutrophication, sediments, over-fishing, destructive fishing, reef mining, aquarium and curio trade, diseases
Wetlands	Reclamation and development
Seagrass beds	Siltation, coastal development, eutrophication, physical disturbance
Coastal lagoons	Reclamation, pollution
Mangroves	Excessive exploitation, reclamation, development, aquaculture
Shorelines	Development, habitat modification, erosion
Watersheds	Deforestation, soil erosion, pollution, habitat loss
Estuaries	Reduced water flow, siltation, pollution
Small islands	Sea level changes, waste management
Continental shelves	Pollution, fishing, dredging, navigation
Semi-enclosed seas	Pollution, coastal development, fishing

1.4.1 Pressures on the Coastal Zone from Natural Forcing

1.4.1.1 *Global Systems and Climate Patterns*

Large-scale phenomena influence climate, including the global "ocean conveyor belt" or thermohaline circulation pattern (Broeker 1994) and, regionally, ENSO (El Niño-Southern Oscillation) in the Pacific Ocean and the NAO (North Atlantic Oscillation) (Fig. 1.7; see Sect. 1.3.3.1). Evidence is accumulating of historical shifts in the patterns and intensities of these phenomena that can influence biotic distribution and diversity and affect coastal processes. The "ocean conveyor belt" influences heat fluxes and greenhouse gases in the atmosphere and its flow intensity may change on various time-scales with major effects on climate and thus parameters such as temperature and precipitation patterns, trade-wind intensity and wave climates (Steffen et al. 2004).

ENSO is driven by major climate patterns in the Pacific but the effects extend to at least Europe and North America where elevated sea level, increased erosion and changes in rainfall patterns have been observed. There are indications of much greater intensities and frequencies of ENSO events over geological time-scales, beyond those experienced in recent years (Bradley 2002). ENSO is known to affect global distribution and concentrations of CO_2.

The potential for change in these global-scale phenomena is well demonstrated. Thus, further and probably dramatic changes in the current level of forcing from these phenomena on many natural and human-related pressures in the coastal zone are likely. Recent major global bleaching events in shallow coral reefs are ascribed to high sea-surface temperatures (Wilkinson 2000), a forcing parameter linked to these large-scale phenomena.

1.4.1.2 *Sea Level*

Sea-level change is an issue of major concern in the coastal zone, particularly for ecosystems and residents in river deltas and low-lying areas, and in small island states. Relative sea level has fluctuated across hundreds of metres at millennial time-scales. The dominant Driver of sea-level change is sea and air temperature. With an estimated rise of 0.6 °C in average global sea surface temperature during the 20th century and a further predicted rise of between 1.5 °C and 4.5 °C over the next 100 years (Houghton et al. 2001), sea-level rise is a phenomenon of vital concern when considering the State of the coastal zone and the potential for changes in both natural systems and human society, now and well through the next century.

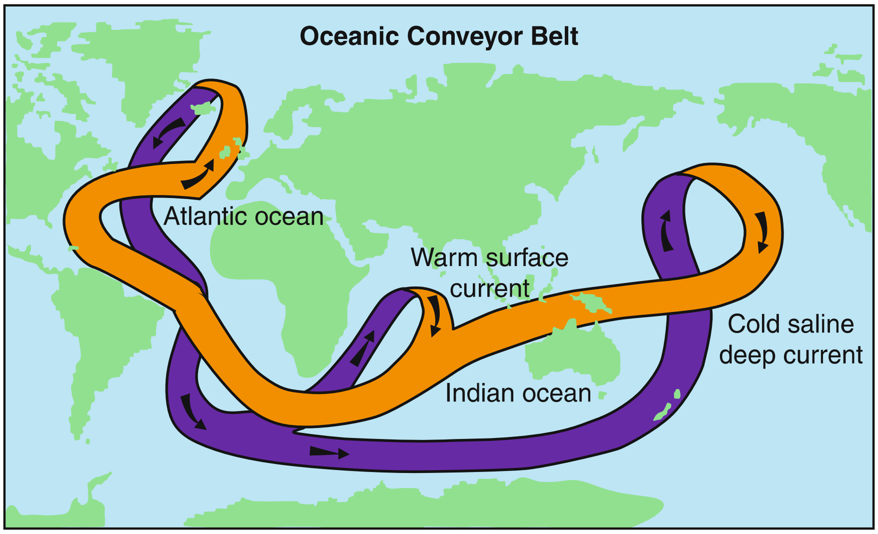
The IPCC has estimated sea level to have risen at rates of 1.0–2.5 mm yr^{-1} over the last century, and modelling scenarios project a further increase in the range of 9–88 cm over the next 100 years (see Sect. 2.2, Chap. 2). Other IPCC projections indicate with high confidence that:

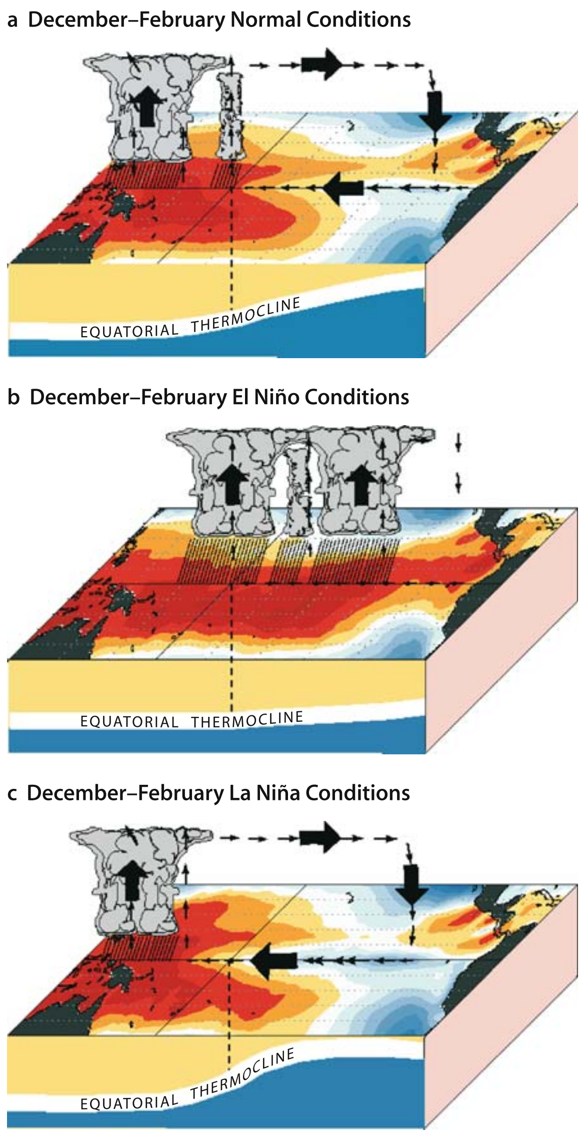
- natural systems will respond dynamically,
- the responses will vary locally and with climate,
- wetlands may survive, where vertical accretion rates are sufficiently nourished by sediments, and
- engineering infrastructure in the coastal zone may be a barrier to the landward dynamics of ecosystems.

Potential impacts include shoreline erosion, severe storm surge and flooding, saline intrusions into estuaries and groundwater aquifers, and altered tidal ranges. The resilience of coastal ecosystems and human habitation to these projected increases in sea level is of vital concern (Arthurton 1998, Klein et al. 2003).

A global network of coastal scientists, engineers and managers has applied a common methodology for the as-

Fig. 1.7.
The coastal zone. Diagram of the global thermohalocline circulation process (*top*) and the El Niño-Southern Oscillation (ENSO) and La Niña processes in the southern Pacific Ocean (*bottom*) (from Steffen et al. 2004, as adapted from Broecker 1991; NOAA, *http://iri.colombia.edu/climate/ENSO/background/basic.html*)





sessment of coastal vulnerability and adaptation to accelerated sea-level rises across regions of the world (Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies (SURVAS), *http://www.survas.mdx.ac.uk/*). An EU-funded project "Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-level Rise" (DINAS-COAST) is expanding the approach, building a CD-ROM-based tool to incorporate quantitative information on a range of coastal vulnerability indicators and to relate these to socio-economic scenarios and adaptation policies at national to global scales (*http://www.dinas-coast.net/*).

Already many coastal regions are experiencing significant increases in relative sea level because of subsidence resulting from isostatic and tectonic adjustments or human activities (see Sect. 2.1, Chap. 2). Taking advantage of new space platforms that measure sea surface levels, a new global program of research is looking to evaluate these and related changes to improve modelling and understanding (Goodwin et al. 2000).

1.4.1.3 *Carbon Dioxide and Greenhouse Gases*

Changes in CO_2 concentration and other greenhouse gases in the atmosphere have implications for the coastal zone directly and indirectly from effects on temperature elevation and climate (Text Box 1.3). Over the last 150 years atmospheric CO_2 has increased by 30% to around 370 ppm – to beyond the maximum levels experienced over the last 400 000 years, as inferred from ice-core records (Steffen et al. 2002; see Fig. 1.4 above). However, current projections suggest that this CO_2 concentration will double over the next 100 years, placing us well outside the range of previous experience; human activities continue to influence this increase (Houghton et al. 2001).

Text Box 1.3. Trace gases (other than CO_2) in the coastal zone

From Pacyna and Hov 2002

The coastal ocean is a source of selected trace gas emissions to the atmosphere. The most important trace gases emitted in appreciable amounts from the coastal ocean include methane, nitrous oxides, dimethyl sulphide (DMS), carbonyl sulphide (COS), and mercury. The production of these gases in coastal ecosystems, particularly estuaries, and the sea-to-air flux have been studied, mostly in Europe. Information on the production and sea-to-air flux of other trace gases in coastal ecosystems is very limited, and it is difficult to draw conclusions on the significance of these fluxes.

Processes of trace gas production and transport from the ocean surface to the atmosphere are complicated and require multidisciplinary studies, including various aspects of biology, meteorology, hydrology, chemistry and physics. The vast majority of efforts to explain production and water-to-air transport have been carried out with the use of models and measurements in the open ocean rather than in the coastal ocean.

Flux rates for transport of trace gases from surface waters to the air are higher for the coastal zone than the open sea, up to several orders of magnitude for some gases (Table TB1.3.1), using the data from the EU BIOGEST project (Frankignoulle 2000) and other literature data. This contribution can be 50% and more for nitrous oxide and COS. The contribution of emissions of these gases from European estuaries to total European emissions is relatively low, except for nitrous oxide.

Limited information on flux rates for methane, nitrous oxide, DMS, COS and mercury in other regions of the globe makes it difficult to assess the coastal contribution on a global scale. First approximation of trace-gas emissions on a global scale indicate that estuaries contribute up to 2%, except for nitrous oxide which is higher. At local and regional scales, emissions in coastal areas can contribute substantially to the total emissions of these gases. Further studies are needed to provide a more accurate understanding of the production and sea-air exchange processes for these gases globally.

Changes of sea-air fluxes of trace gases in the coastal zone are directly and indirectly dependent on the changes to socio-economic and natural drivers of environmental change in coastal ecosystems. Sea-to-air fluxes form one of the pressures on the coastal ecosystem. Direct relationship between socio-economic drivers changing the coastal ecosystem and the fluxes of trace gases from the coastal ocean to the air can be illustrated through the enhanced input of various trace gas precursors, including organic matter, nitrates, ammonium, sulphates and mercury deposited to the sea on particles from the air or transported by rivers to the coast. Indirect relationships between drivers and the fluxes of trace gases can be analysed, taking into account the natural drivers of environmental change in the coastal zone, such as climate change and its consequences including biodiversity reduction, habitat loss and modification.

Table TB1.3.1. Fluxes of biogases from estuaries and their global contribution

Compound	Estuary to open ocean flux rate ratio	Estuary emissions in Europe (kt yr^{-1})	Estuary contribution to total European emissions (%)	Coastal sea contribution to the total sea-to-air flux (%)	Coastal sea contribution to global emissions (%)
CH_4	~1000	580	2.5	up to 30	0.2–2.0
N_2O	~100	120	9.4	up to 60	2.0–15.0
DMS	1–3	60 (as S)	1.0[a]	up to 10	2.0[a]
COS	10–100			up to 50	
Hg	~10	12×10^{-3}	3.5	up to 20	~0.5

[a] Contribution to the total European or global emissions of sulphur.

Vital issues of research and debate include changing CO_2 concentrations, impacts on terrestrial crops and agriculture, biological processes of the ocean (the major sink for global atmospheric CO_2), climate, temperature regimes and marine coastal systems (Walther et al. 2002, Buddemeier et al. 2004, Steffen et al. 2004, *http://www.globalcarbonproject.org*). Changing patterns of productivity in marine waters are forecast (Fasham 2003), while a decrease in calcification rates by as much as 30% has been projected for coral reefs in response to a doubling in CO_2 concentration (Kleypas et al. 1999, Guinotte et al. 2003; see Text Box 3.2, Chap. 3).

1.4.2 Pressures on the Coastal Zone from Human Forcing

1.4.2.1 *Land-based Resource Uses*

1.4.2.1.1 *Agriculture*

While the conversion rate of forests and grasslands to managed agricultural systems is not as rapid as in the mid-20th century (Wood et al. 2000), the intensification of cropland and agricultural production is increasing through application of fertilisers, pesticides and herbicides and the use of irrigation or drainage. Alienation of wetlands (mangroves, salt-marshes, dune systems) continues as sugarcane, rice and fish mariculture are expanded regionally throughout the world. Freshwater used for irrigation accounts for significant changes in river flows affecting, *inter alia*, coastal sedimentation processes and river delta maintenance (see Chap. 2). For example, in the Nile River, flows reduced by more than 90% with concomitant coastal erosion and changes in the trophic systems of the coastal receiving waters (Nixon 2003).

Emissions and inputs from agriculture are a significant source of pollution to the coastal zone and to the atmosphere. Global production of nitrogen fertilisers by humans now exceeds the natural rate of biological nitrogen fixation in terrestrial ecosystems (Bouwman et al. 1995, van Drecht et al. 2001). Much of the increased nitrogen load finds its way into surface and artesian waters, thus elevating nutrient loads in the coastal zone (Vitousek et al. 1997, Kroeze et al. 2001). The development of the superphosphate industry in the late 19th century brought a concomitant rise in industrial production and global use of phosphatic fertilisers. Recent estimates suggest that P storage in freshwater and terrestrial systems has almost doubled, and fluvial drainage of P to coastal seas has risen nearly 3-fold, since pre-industrial times (Bennett et al. 2001). Use of fertilisers continues to increase from levels of about 150×10^6 tonnes per year in 1990 to projected use in excess of 200×10^6 tonnes per year within the next decade (Bumb and Baanante 1996, cited in WRI 2000). Recent assessments by UNEP (Munn et al. 2000, GESAMP 2001) considered the global nitrogen overload to be one of four major emerging environmental issues for effects on eutrophication, human health and general water quality of fresh and marine coastal waters and within allied ecosystems.

1.4.2.1.2 *Forestry/Deforestation*

Forests yield valuable timber and non-wood products (food, cash crops, industrial raw materials) for human society. Estimates for global trends in deforestation are uncertain (Matthews et al. 2000), but significant tracts of forest continue to be lost to deforestation in river basins in many parts of the world, reducing watershed protection and increasing erosion. River flow, water quality and coastal ecosystems are affected through increased sedimentation rates and elevated nutrient inputs (Scialabba 1998). Major re-forestation projects are being carried out in some regions, especially in developed countries, as a move to increase carbon sequestration from atmospheric CO_2 as well as for improved management of land and riparian zones.

1.4.2.1.3 *Damming and Irrigation*

Globally, more than 41 000 large dams (> 15 m high) are in operation impounding 14% of runoff. This represents a 7-fold increase in dams built over the last 50 years, and numbers are still increasing (WRI 2000). These provide hydroelectric power, industrial and other human needs including flood mitigation. Small reservoirs and dams in local catchments number in the millions. Globally these impoundments may account for sequestration of almost 2 gigatonnes C per year – equivalent to the "missing carbon" in current global models (Smith et al. 2001).

The effects of damming and irrigation on water flow are manifested in multiple examples of coastal erosion in response to reduced sediment flows throughout all regions of the world (Milliman 1997). Such effects impact coastal ecosystems by increasing saline intrusions, diminishing coastal groundwater discharge and reducing biodiversity. Freshwater inputs reduced by construction of impoundments in the catchment of rivers in South Africa altered the patterns of productivity, biodiversity and ecosystem properties of estuaries (Baird and Heymans 1996). More subtle pressures through changes in water quality include reduced silicate loads to coastal waters (Conley et al. 1993) with a resultant shift in phytoplankton communities from dominantly diatoms to flagellates (e.g., Black Sea, Humborg et al. 2000). Ramifications for coastal biogeochemical cycles include sequestration of carbon and acceleration of eutrophication processes, while trophic structures in estuaries and coastal seas that depend on land-derived nutrient inputs are also affected; for example, the Bay of Bengal and other areas receiving major river plumes, such as the receiving waters of the Mississippi, Amazon and Nile river flows (Turner et al. 1998, Ittekkot et al. 2000, Nixon 2003).

1.4.2.2 *Industrial and Urban Development*

1.4.2.2.1 *Industrialisation, Urbanisation and Wastes*

The location and intensity of development of the coastal zone to meet urban and industrial needs is mirrored by the global distribution of the population. Both the intensity and the areal extent of these developments are increasing concomitantly with population. The resultant pressures and effects on the natural resources and ecosystems can be measured through assessments allied with integrated coastal zone management initiatives (e.g., Jickells 1998, Ducrotoy and Pullen 1999).

Nutrient and contaminant wastes, atmospheric loads, sewage and other urban and industrial materials including oils and detergents have been identified as continuing global concerns (GESAMP 2001). The GESAMP report noted some recent advances in control of contaminant and point-source discharge and diminished pressures in response to environmental management and technological solutions.

Technological and legislative advances for controlling substance emissions are increasingly associated with industrialised locations in the developed world and in some localities in the less-developed world. The destruction of coastal habitats by the insidious spread of urban development remains a major issue. Megacities have specialist footprints of influence which may haverequire unique management approaches. For example, Paris has significant impacts measurable 75 km downstream in the River Seine basin and water quality remains affected 200 km downstream (Meybeck 1998); even upstream, the "Paris effect" is detectable, since the water demand and the flood protection needs of the city have resulted in extensive river management and reservoir constructions affecting flow patterns. The advance of "the global economy" is raising new coastal management concerns about local industrial performance and environmental impacts, especially by multinational companies that operate in a range of locations around the world, with differing environmental standards.

1.4.2.2.2 *Reclamation and Shoreline Development*

The extent of the conversion of natural ecosystems – wetlands, estuarine and coastal habitats – by land reclamation and engineering structures (sea walls, revetments, groynes, breakwaters) generally reflects population pressures and attempts to protect coastal infrastructure from storms and other high-energy events (Arthurton 1998, Burke et al. 2001). Construction of road causeways and shoreline ribbon developments for tourism facilities and industries adjacent to marine transport infrastructure often destroy habitats serving as natural fisheries and bird nurseries. Hard structural engineering options including flood mitigation barrages and dykes (e.g., the Ijsselmeer in the Netherlands) affect water quality, habitats and sediment processes.

Coastal structures can modify sediment transport along a coast, resulting in increased local and displaced erosion, which then requires mitigation by costly and continuous sand nourishment schemes. This may lead to intensified dredging from near-shore and riverine systems. The application of hard engineering structures as an option for coastline defence can preclude subsequent alternatives for coastal management of dynamic coastlines (e.g., Pethick 2001).

While shoreline protection measures through coastal armouring continue around the world, natural mitigation services are more frequently included in shoreline planning. In Cuba, recent tourist developments are constrained behind a coastline setback zone of several hundreds of metres. For the highly-engineered coastline of the Netherlands, new policy strategies encompass "building with nature" instead of "working against nature" (de Vries 2001); coastal flats and sand-dune systems are now being set aside from human development and maintained in order to act as natural dynamic buffer zones.

1.4.2.3 *Transportation*

Transportation by sea is the life-blood of global commerce, with 95% of world trade moved by shipping. Many port and infrastructure developments require dredging, with associated mobilisation and distribution of sequestrated nutrients and contaminants, while engineering structures modify estuaries and coastal shorelines. Port facilities engender further development of road and rail transportation systems and allied growth in population, which affect coastal land-use patterns, natural resources, environmental goods and services and other ecosystem amenities.

The translation of products and minerals from one global location to another has impacts and management ramifications for waste and landfill, pollutants and contaminants. One example is the use of the food-chain toxic tributyl tin in anti-fouling paints, which in recent years has been greatly restricted by conventions (within the International Maritime Organisation) and by national or local management regulations.

Ballast water is responsible for biological species transfer, particularly of pathogens, spores and cysts that can result in harmful algal blooms and human diseases. Introduction of non-indigenous biological species can have devastating effects on receiving systems, affect local fisheries and aquaculture economies and impact on public health. Measures are being taken to minimise ballast water transfers of living propagules (*http://www.imo.org*) and to reduce further negative impacts. Treatment of ballast water is a major issue for the International Maritime Organisation, the International Council for the Exploration of the Seas and port authorities.

Transient population shifts closely allied with tourism and commerce affecting coastal zones require transport. Infrastructure of airports, burned-fuel emissions and dumping of excess fuel over water (NRC 2002), ground transportation systems and associated settlements to service air transportation facilities affect both the natural environment and societal structures (see Text Box 2.10, Chap. 2)

1.4.2.4 *Mining and Shoreline Modification*

Mining for minerals and construction materials, oil and gas extraction and dredging of sediments have a multitude of environmental consequences including dispersal and resuspension of sediments, bathymetric changes, altered groundwater flows, loss of habitats and fisheries and altered natural sedimentation-erosional processes that affect shoreline stability.

Dredge materials account for 80 to 90% by volume of materials dumped into the ocean; several hundred million cubic metres of coastal sediments are dredged worldwide annually. The effect of sediment extraction remains an issue in many parts of the world (see Text Box 1.4).

The coastal zone is a major focus for oil and gas extraction with concomitant ecosystem impacts. In recent years, the application of new extraction techniques, spill management and contingency plans has seen a relative decline in oil spills (Burke et al. 2001, Summerhayes and Lochte 2002). However, there are mounting concerns about land subsidence, erosion, and allied impacts on coastal ecosystems resulting from subterranean removal of oil and gas (and also groundwater). For example, along the West African coast, the natural barrier-lagoon structure is undergoing subsidence and erosion (among other pressures) which are causing shoreline retreat at a rate of about 25–30 m per year, with potentially huge impacts on human habitation and ecosystems (Awosika 1999).

1.4.2.5 *Tourism*

Tourism is a benefit to the economies of most countries, generating US$ 4.9 trillion and about 200 million jobs worldwide, and has grown enormously over the last decade (WTTC 2003, *http://www.wttc.org*). In many countries, especially small island states, it is the major sector of the economy. As the coastal zone is a major focus for global tourism, economic and societal benefits are invariably offset by impacts on the environment, leading to doubts about the sustainability of tourism in some locales. Coastal development and localised population expansion, often seasonal, are legacies, while tourist activities frequently place direct and poorly-regulated pressures and impacts on the coastal system. These pressures depend on the type and style of tourism (Pearce 1997).

Pressures from tourism encompass and exacerbate the array of factors associated with urban developments and expand elevated population densities into new localities in the world. Concepts of sustainable tourism have been introduced into the industry by the World Tourism Organisation and related bodies to enhance industry management and awareness (Moscardo 1997). Demands for eco-tourism and a quality environment are apparently increasing and there are examples of well-managed tourism facilities and activities, such as in the Great Barrier Reef region where partnerships between industry and environmental management agencies ensure quality of visitor experience and sustained ecosystems (Crossland and Kenchington 2001). However, societal support and infrastructural developments to underpin tourist populations continue to exert negative pressures on many coastal systems globally.

Text Box 1.4. Sediment extraction in the North Sea

Russell K. Arthurton

The sedimentary nature of the North Sea (a relatively enclosed coastal sea) has provided a source of aggregate for building materials, especially from the extensive sand and gravel beds in the southern area and along the eastern coast of England. Direct impacts of coastal building and development on coastal integrity are most apparent in the shallow southern North Sea where construction and maintenance of dykes, artificially maintained dunes and underwater barriers have traditionally required skilled engineering. With an increase in the use of soft-engineering techniques such as beach nourishment for coastal protection, offshore sands such as those forming the Race Bank area off eastern England provide material for beach replenishment of coastal areas. The intense longshore drift along the coast of the Netherlands also requires constant beach nourishment.

The marine aggregate extraction industry (habitat excavation by dredging) in the North Sea is well-established and expanding in the shallower regions, having grown from 34×10^6 m^3 in 1992 to 40×10^6 m^3 in 1996. Extracted materials include shell and the calcareous red alga, *Lithothamnion* sp. The potential physical impacts of sand and gravel extraction are site-specific and depend on numerous factors including extraction method, sediment type and mobility, bottom topography, and bottom current strength. Suitable materials are unevenly distributed and should be considered as finite, except for additions from coastal erosion and, locally, river discharge. Long-term forecasts for supply are required and international co-operation needs to be envisaged for sustainable use of the resource.

1.4.2.6 *Fisheries*

Global fisheries have high socio-economic significance, providing more than 6% of the protein consumed by humans, and are especially important in developing country economies and food supplies (see WRI 2000). Fisheries yields have declined from almost 100 million tonnes to about 90 million tonnes annually over the last decade. While global wild-stock catches have been declining, pressures have not; even in the mid-1990's, fleet capacity was estimated as being 30–40% greater than need (Grainger and Garcia 1996).

An estimated 90% of the marine fish catch comes from the coastal zone (freshwater fisheries are important regionally) with about 30% currently derived from aquaculture. Aquaculture, with associated natural habitat destruction and pollution impacts, has grown substantially over the past three decades and, in many parts of the world, aquaculture in coastal and marine waters is the only growth sector within marine fisheries. While most of the finfish production stems from fish species low down the food chain, a growing proportion comes from higher trophic levels.

Over-fishing is a major problem for most regions of the world and the practice of "fishing down the trophic levels" (Pauly et al. 1998, Pauly and Maclean 2003) is a major concern for ecosystem function as well as for socio-economic performance of the fisheries system (see Text Box 1.5). The activity of fishing itself can impact on coastal ecosystems in several ways. The removal of piscivorous fish species, for example, not only can affect the age and size composition of the exploited species, but also can impact on energy flow pathways in the ecosystem. Life-history changes, increased growth rates and a lowered age at maturity have been reported in plaice (*Pleuronectes platessa*) and cod (*Gadus morrhua*) in the North Sea (Lindeboom et al., in press). It has been shown that through selective fishing, even the genotypic characteristics of exploited species have changed (Walker 1998, Ducrotoy et al. 2000).

In addition to over-fishing, fishery operations can have a destructive physical impact on the seabed and can affect population levels of non-target species through incidental catch; these problems are of particular significance for cetaceans, sea turtles and seabirds such as the albatross in different parts of the world. Direct effects of trawling and by-catch issues in coastal systems are well-documented and show major impacts on ecological structure and influences on biogeochemical cycles (e.g., Sainsbury et al. 1997, Kaiser and de Groot 2000). Poison and explosive fishing techniques used in many coral reef regions cause reef destruction and trophic alterations (Wilkinson 2000). Commercial and recreational fisheries in coral reefs and associated systems may be leading to symptoms of eutrophication by removal of herbivores (see Szmant 2001).

Changes in climate, such as the North Atlantic Oscillation, appear to be affecting fish distributions and their spawning patterns (ICES unpublished reports 1999). These changes are coupled with pollution effects on fish and bioaccumulation of pollutants (GESAMP 1996).

The expansion of aquaculture through the last decade, particularly in Southeast Asia and China, has major ramifications for coastal zone management from allied pressures imposed on an array of ecosystems, including supply of stock from the wild, restriction of water flows in estuaries, benthic system changes, physical and chemical changes in sediments, oxygen depletion and coastal eutrophication.

Overall, the long-term indirect effects of fisheries on coastal marine ecosystems concern the trophodynamics of the system, viz., the efficiency of energy transfers be-

Text Box 1.5. Fish population changes in the North Sea

Han Lindeboom

The rich North Sea grounds support one of the world's most active and intensive fisheries, with highest landings per unit area in the North East Atlantic. The North Sea fishery removes 30–40% of the annual biomass of exploited fish species (Gislason 1994). Landings were highest in 1996 when 3.5×10^6 t were fished. Stocks of herring, cod, mackerel and plaice were fished beyond sustainable biological limits in the second half of the 20th century and the extensive over-fishing has forced drastic managerial measures to reduce the damaging effects of the fishing practices on both biomass and structure of fish populations. For herring, this led to a notable recovery. In 2002 the EU imposed an 80% cut in quotas of cod, the socio-economic consequences of which will be extremely painful for the industry. In some cases (e.g., cod, plaice and starry ray), the gene pools have been selected in favour of smaller animals reproducing at an earlier age, hence inflicting an impact at ecosystem level.

On the other hand, there are higher numbers of the seabirds which survive on discards and offal. The total mass of discards in the German Bight in 1991 was estimated at 36×10^3 t fish, 58×10^3 t starfish and 800 t swimming crabs; the number of individuals included 420 million fish, 5 800 million starfish and 120 million swimming crabs. More than 8 kg of unwanted animals were discarded per kg of marketable fish. Beam trawling and other demersal methods have affected benthic communities and trophic interactions (Jennings and Kaiser 1998) and there is increasing concern about the loss of juvenile fishes and the shift in age distribution towards younger fish.

Fishing also causes mortality of non-target species of benthos, fish, seabirds and mammals. In Dutch waters, ray populations have been annihilated. Heavy towed gears disturb the uppermost layer of the seabed, while gillnets accidentally entangle seabirds and marine mammals (Kaiser and Spencer 1996). The high fishing pressure within the North Sea gives cause for concern regarding the loss of mature and breeding fish populations as well as other ecosystem changes (see, for example, Jennings and Kaiser 1998). The creation of Marine Protected Areas, effort reduction and more selective gear are seen as major managerial tools which may turn the tide.

tween trophic levels. Trophic changes in predator-prey relationships and energy flows as well as habitat alterations have clearly created new conditions in many coastal systems. Genetic changes and selection of individuals and species adapted to such new environmental conditions are potentially major imposts by humans on natural ecosystems; focussed research needs to gauge any harmful consequences, including loss of biodiversity (Ducrotoy 1999).

Coastal ecosystems are vulnerable and subject to many development activities by humans. The effects of such activities and their eventual impact on coastal systems will vary within and among systems. Challenges facing coastal scientists and managers include assessment of the magnitude of these impacts and development of appropriate remedial conservation policies. For example, it can be predicted that a reduction in freshwater input into an estuary will affect the diversity and productivity of the constituent plant and animal communities. The magnitude of the predicted changes, however, is difficult to quantify; even more so, the response of the system as a whole. These changes can be analysed in retrospect and the response of the system assessed. Baird and Heymans (1996), for example, found that despite large fluctuations and divergent trends in abundance, productivity and diversity of individual components of an ecosystem following severe freshwater reduction in an almost pristine estuary, only marginal changes were apparent at the whole-system scale.

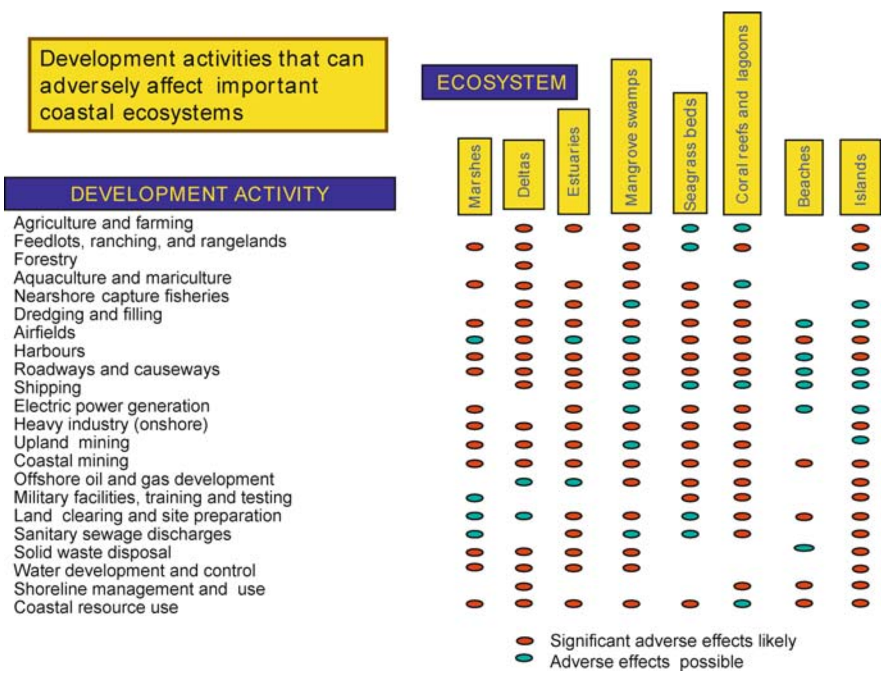
The matrix in Fig. 1.8 summarises the impacts of development activities on coastal ecosystems and provides a subjective index of the potential severity of these in the coastal zone. The matrix illustrates that few systems are immune to development activity and that invariably any kind of development activity impacts on more than one system. What the matrix does not show is the unique characteristic of the Anthropocene Age: the rapidity of changes inflicted by humans on natural systems.

1.4.3 Economics and Coastal Zone Change

The resources, products and amenities of the coastal zone are crucial to the societal and economic needs of the global population. Equally, the natural functions of wetlands, forests, agricultural regions, estuarine and coastal marine ecosystems play a vital role in Earth's function – for example, wetlands act as system "kidneys" for nutrient transformations and exchange, and as variable time-scale sinks and reservoirs for materials storage (Ibanez and Ducrotoy 2002). These benefits from the coastal zone are obvious for both society and nature, and are frequently the focus of societal conflicts at local and sometimes regional scales; conflict resolution is usually addressed through integrated coastal zone management approaches (e.g., Burbridge 1999, von Bodungen and Turner 2001).

The importance of the coastal zone and its constituent ecosystems is recognised by society from ecological, economic, social and aesthetic points of view, but the more recent recognition of the consequences of human activities on coastal zone ecosystems has led to increased interest in environmental economics and estimations of the cost of ecosystem degradation and rehabilitation. For

Fig. 1.8.
The coastal zone. Relationship between development activity and coastal systems



example, the 1997–98 ENSO event was associated with widespread coral-reef bleaching (Hoegh-Guldberg 1999, Wilkinson 2000). Although many coral reefs that had suffered mass mortality are showing signs of recovery, the socio-economic impacts have been severe. The loss of coral reef habitats has probably exacerbated over-fishing in regions where this was already a problem. Income from coastal tourism has probably declined, and coastal erosion has increased in areas where degrading coral reefs formed lesser barriers to wave action (e.g., Sri Lanka). Estimates of the economic losses in the Indian Ocean alone due to coral reef losses range from US$ 700 to US$ 8200 per hectare over 20 years (Wilkinson et al. 1999).

Globally, the societal importance of the coastal zone can be related to two key elements, namely: (*1*) ecosystem goods (de Groot et al. 2002) and services (Daily 1997) concentrated in coastal marine and estuarine systems and (*2*) the growing coastal human population and its demands on ecosystem goods and services, including those of the adjacent river basins (Costanza et al. 1997, Hinrichsen 1998, Daily and Walker 2000).

Coastal ecosystems provide a wide range of goods and services which constitute the natural capital of the coastal zone. The coast provides two kinds of benefits: direct and indirect. Direct benefits include goods and services that are produced by coastal ecosystems such as fish for human consumption, kelp used for fertilisers, coastal tourism, mining (e.g., for diamonds, titanium) and timber-harvesting. Indirect benefits are ecological functions performed by coastal ecosystems: for example, wetlands detoxify wastewater, the land-sea interface creates a mild climate, the recycling of essential elements (e.g., C, N, P, Si), the upwelling process with its biological consequences, and erosion control. Environmental economists sometimes include other benefits (Ledoux and Turner 2002). For example, an option value that reflects the benefit of conserving resources for the future, an existence value that illustrates the benefit from coastal resources simply because they exist, and a bequest value that reflects the benefit of knowing that the preserved natural environment and its resources will be passed on to future generations.

The demands on ecosystems to generate and provide commercial goods, recreation and living space and to receive, process and dilute the effluents of human settlements will continue to grow. For example, land-based sources account for about 80% of the annual input of contaminants to the oceans (UNEP 1995). At the same time, coastal ecosystems are experiencing unprecedented changes that affect their capacity to provide these services and support valuable resources. The phenomena of interest include sea state, surface currents, sea-level rise, coastal erosion and flooding, habitat modification and loss (e.g., coral reefs, seagrass beds, tidal wetlands), loss of biodiversity, oxygen depletion, harmful algal bloom events, fish kills, declining fish stocks, beach and shellfish bed closures and increasing public health risks (Table 1.4). Apparent increases in the occurrence of these phenomena indicate profound changes in the capacity of coastal systems to support living resources.

Such changes make the coastal zone more vulnerable to natural hazards, and make more costly the management of its resources in a sustainable manner. The conflict between commerce, recreation, development and the management of ecosystems and their living resources will become increasingly contentious and politically sensitive in the absence of realistic coastal zone management policies and mechanisms to detect and predict the impact of environmental changes on the socio-economic fabric of the coastal zone. Informed decision-making is vital in this context (von Bodungen and Turner 2001).

Putting a value on human resource use and natural environmental services of the coastal zone has been a topic of increasing effort over the last decade. It has proven difficult and has frequently led to contentious outcomes, often because of differences between the models, metrics and methods (especially in dealing with time-scales) of the more traditional economic and social science disciplines and those of the evolving approach of ecological economics (Jickells et al. 2001). Monetary units are the more commonly used measures of both approaches but there is well-founded debate on both the rigour of each approach (and levels of uncertainty) and the ability of monetary terms to capture and measure human perceptions and ecosystem functions (Turner 2000, Faber et al. 2002).

Despite this uncertainty, it is clear that the global coastal zone has a high value. For example, Costanza et al. (1997) concluded that the global value of ecosystem services was in the order of US$ 33 trillion per annum, or about 1.8 times the global GNP. They further estimated that marine ecosystems provided about 63% of these goods and services, and that coastal ecosystems, which comprise about 8% of the world's surface, provided 43% (or US$ 12.6 trillion per annum) of the global total. Wilson et al. (2004) have recently updated these values, estimating that the coastal zone has a total economic value of about US$ 17 trillion per annum and provides 53% of the total annual ecosystem service value of the world. The greatest value for a single ecosystem service was ascribed to nutrient cycling. On a smaller scale, Glavovic (2000) calculated that the direct and indirect benefits derived from the coastal zone of South Africa were in the order of US$ 22 billion and US$ 18 billion per year, respectively; combined, these services comprised about 63% of the country's GDP. These and other analyses (e.g., Daily and Walker 2000) clearly illustrate the value of coastal ecosystems and their importance to society on global and local scales.

Irrespective of any debate on details and the rigour of the estimates, it is generally agreed that ecosystem coastal services are of high value. Recent attempts to gain a measure of the various economic sectors of the global economy show similarly high values for the coastal zone. Global tourism was estimated at US$ 4.9 trillion per year (WTTC 2003), most of which takes place in the coastal zone. Fisheries exports are > US$ 50 billion per year (FAO 1999). Around 1 billion people depend on fish as a source of protein (Laureti 1999 cited in WRI 2000), an estimate not normally captured in the fisheries export monetary values.

The research approaches for valuation and measurement of benefits from the coastal zone offer a field of challenge that is attracting much current effort (Turner et al. 1998, Voinov et al. 1999, Gren et al. 2000, Aguirre-Munoz et al. 2001). Modelling approaches and scaling mismatches between model elements in particular are being tackled (e.g., Talaue-McManus et al. 2001), in addition to resolution of more basic parameters such as temporal parameterisation and metrics for expression. It seems likely that future assessments will not only ascribe even greater gross value to the coastal zone, but new tools should contribute significantly to improving estimates of trade-offs and options for integrated coastal management decisions (Ledoux and Turner 2002).

1.5 Measuring Change and Status of the Coastal Zone at the Global Scale – LOICZ Approaches and Tools

The coastal zone is a domain of convergence for terrestrial, oceanic and atmospheric forcings and human influences. The heterogeneity in the intensity of these forcings and the diversity of human influences provide a fine spatial tapestry of biophysical processes interacting with human society. These are associated with a dynamic for change across a range of temporal scales extending well beyond human life spans. Consequently, we are severely constrained in our ability to realistically describe and model the extraordinary array of interactions in a detailed and strictly quantitative manner and to meet all expectations of scalar assessment within Earth's coastal systems. Most coastal zone assessments are at local and sub-regional national scales. They are often unique (or one-off) evaluations, frequently addressing single issues of forcing and are usually founded on the application of only one or two traditional scientific disciplines, for example, oceanography, biology, sociology, demography or economics. Rarely are multi-disciplinary approaches used to address holistic issues of status and change in the coastal zone.

Our approach for measurement of changes in the coastal zone has needed to encompass elements that are approximate, semi-empirical, iterative and evolutionary. The LOICZ approach takes two forms. First is the development of horizontal and, to a lesser extent, vertical material flux information and models across continental basins and through regional seas to continental shelf margins. This has been based on our understanding of biogeochemical processes for coastal ecosystems and habitats and their interactions with the human dimensions. Second is the development of ways to incorporate scaling of the material fluxes, spatially from local to global levels and across decadal temporal scales. While we have made good progress on the first element, the second remains a challenging activity for the research community.

We have recognised that there is a large amount of existing (secondary) data and work being carried out around the world on coastal habitats and ecosystem processes at a variety of scales, but that there are gaps in this work. Hence, LOICZ has sought to build networks of global researchers in order to capture and initiate the gathering of new scientific data. LOICZ has established a number of thematic approaches and tools to address material fluxes and human dimensions in the coastal zone. These have provided regional and global descriptions of:

- material fluxes and human interactions across various spatial (and limited temporal) scales,
- biogeochemical transformations in estuaries and coastal seas (generally from locally-scaled data),
- coastal fluxes at regional and global scales by consistent up-scaling methods (typology),
- socio-economic implications of changes in coastal ecosystem status,
- river basin fluxes of materials and interaction with pressures derived from natural phenomena and human activities, and
- key global change phenomena, such as sea-level and global warming, and submarine groundwater discharge (*http://www.loicz.org*).

New tools include concept developments and new research, adaptation and extension of existing methodologies and scientific assessment approaches (see LOICZ Reports & Studies publications, Appendix A.1). Supportive and additional information was obtained from new research commissioned, sometimes by LOICZ but usually by regional and national agencies in response to initiatives by the LOICZ community. The LOICZ network of scientists has collaborated in evaluating and synthesising the results from commissioned research and other emergent data into regionally- and globally-scaled information about the coastal zone. Some of the key tools developed by LOICZ described below form the basis of the approach for many of the thematic assessments described in detail in subsequent chapters.

1.5.1 Biogeochemical Fluxes of C, N and P

The questions of interest to LOICZ and IGBP are:

- Globally, is the net metabolism of the coastal zone a CO_2 source or sink?
- How is this net trophic status changing in response to local human intervention and global environmental change?
- Given the spatial heterogeneity of the coastal zone, what is the spatial distribution of net metabolism in the coastal zone?

LOICZ has implemented an approach for evaluating biogeochemical processes for C, N and P in the coastal zone (Gordon et al. 1996, Smith 2002) in tandem with the development and application of a scaling or typological tool and global datasets, (see Sect. 1.5.2 below).

The issue of carbon and its biogeochemical cycling is central to this dual LOICZ approach. A major target is to determine the relative poise of the coastal zone with regard to net carbon flux by answering the question:

- Is the coastal zone an autotrophic or a heterotrophic global compartment? (Holligan and Reiners 1991, Pernetta and Milliman 1995).

A body of literature argues that the coastal zone is heterotrophic but this conclusion remains controversial (see Chap. 3). Although the heterotrophy argument has been supported by some researchers, other workers have argued that coastal systems are presently autotrophic. There is evidence that some coastal ecosystems are autotrophic, which is to be expected in systems receiving higher discharges of inorganic nutrients relative to organic loads.

The LOICZ approach has been directed at existing (secondary) data from individual estuaries and coastal seas. It was felt that insufficient time and resources existed in the lifespan of LOICZ to collect an adequate amount of primary data to address this question at a global scale. Further, it was recognised that there are very few sites around the globe with direct estimates of net carbon metabolism for the entire estuarine or coastal sea system. Thus, net metabolism has been inferred indirectly, via relatively widely available data on nutrients in specific coastal ecosystems. Using secondary data for each estuarine site or coastal sea, a water budget and salt budget were constructed, N and P budgets were derived (mostly reliant on dissolved inorganic N and P data) and stoichiometric calculations yielded net metabolism values for the system.

The principle of this analysis is as follows. Net carbon metabolism can be represented simplistically by the following equation:

$$CO_2 + H_2O \xleftrightarrow{[p-r]} CH_2O + O_2 \qquad (1)$$

where $[p - r]$ represents the difference between primary production (the forward reaction, p) and respiration (the reverse reaction, r). This difference represents the Net Ecosystem Metabolism (NEM) of the system and describes the role of organic metabolism in that system as a source or sink of CO_2. The formation of organic matter via primary production also sequesters nutrients (notably nitrogen and phosphorus) along with carbon; oxidation of that organic matter (respiration) releases nutrients. For any nutrient, Y, taken up in the ratio α with respect to carbon, Eq. 1 can be modified as follows:

$$CO_2 + H_2O + \alpha Y \xleftrightarrow{[p-r]} CH_2O \cdot \alpha Y + O_2 \qquad (2)$$

The familiar Redfield C : N : P ratio of 106 : 16 : 1 would give α values of 6.6 and 106 for N and P in planktonic systems (Redfield et al. 1963).

Equation 1 greatly simplifies reality, for three major reasons. First, use of the equation to estimate NEM assumes that the forward and back reactions (that is, p and r) are based on the same value of α. Second, it is assumed that α is known. Third, it is assumed that reactions of Y not involving this simple stoichiometry are minor.

Lacking data to the contrary, the first two assumptions (constant and known value for α) usually are addressed by the use of the Redfield ratio. With more detail in any particular system, these assumptions can be fine-tuned. The third assumption (minor reaction rates in the system not conforming to the simple Y : C stoichiometry) is perhaps the most critical. In the case of P, inorganic sorption and precipitation reactions clearly occur. When NEM is near 0, these "non-stoichiometric reactions" probably do cause error; this is unlikely to be a serious problem when NEM is well removed from zero. In the case of N, inorganic reactions are probably usually minor. However, the processes of nitrogen fixation (i.e., conversion of N_2 gas to organic N) and especially denitrification (conversion of NO_3 to N_2 and N_2O gases) are likely to be of great importance in many benthic systems. Therefore, this simple stoichiometric approach clearly will not work for N in such systems.

This contrast between P and N stoichiometry leads more or less directly to the LOICZ approach. Budgets of the delivery of dissolved P and N to coastal aquatic ecosystems, minus the export of dissolved P and N from these systems, allow estimates of net dissolved N and P uptake or release by these systems. For the most part, these dissolved nutrient budgets are based on water and salt budgets to establish the advection and mixing of water in these systems. Thus, the dissolved N and P are said to "behave non-conservatively" with respect to water and salt flux. The non-conservative behaviour of dissolved P (scaled by the proportionality constant α) is used as a simple estimate of NEM. The difference between the expected non-conservative behaviour of dissolved N, according to this simple model and the observed non-conservative behaviour, is an estimate of the difference between nitrogen fixation and denitrification [nfix – denit].

Where possible, each of these rates (water exchange, [$p - r$], [nfix – denit]) was compared with independently obtained data; sometimes the rates were close to one another, sometimes they were not. Moreover, the estimate of NEM was compared, where possible, with primary production (p), and was typically less than 10% of primary production. Thus, like the ocean, the role of the coastal zone as a source or sink of CO_2 is represented by only a relatively small fraction of the gross production of the system.

The resultant biogeochemical budgets and inferred rates of net metabolism represent site-specific estimates of metabolism in the coastal zone. More than 200 site-specific budgets now form a global nutrient and carbon inventory (*http://data.ecology.su.se/MNODE*). The budgeting approach has evolved from its initial description (Gordon et al. 1996) during implementation by LOICZ (Talaue-McManus et al. 2003), with the inclusion of a number of sub-models allowing assessment of, for example, freshwater and nutrient inputs (San Diego-McGlone et al. 2000). Scientists from around the world have contributed site budgets to a central database (*http://data.ecology.su.se/mnode/*) with review for quality control imposed before public listing on the web site. A series of regional workshops (see Appendix A.1), convened by LOICZ and supported by a UNEP GEF project, provided opportunities both to build a network and train scientists in the budgeting approach and to develop a global spread of budgeted sites. Details of application and synthesis of the budget approach are described in Chap. 3.

A major challenge has been to extrapolate from the individual budget sites to the global coastal zone and this has been approached via the development of a "typology," or classification, of the global coastal zone (see Sect. 1.5.2). The budgeted sites were mapped in association with their catchment(s) at 1-km scale to provide complementary data on the terrestrial parameters that influence coastal systems, e.g., climate, population, catchment area.

1.5.2 Typology Approach to Scaling and Globalisation

A primary LOICZ objective was to describe the role of the coastal zone in critical biogeochemical fluxes (C, N, P). These fluxes must be understood at global spatial scales, and at temporal scales up to and including those of climate variability and change. Currently, there are relatively few measurements of coastal zone fluxes, and their spatial and temporal coverage is limited. As a practical approach to developing and improving quantitative estimates of coastal zone fluxes at all scales, LOICZ addressed the upscaling of flux measurements by coastal zone typologies (Talaue-McManus et al. 2003, see Chap. 3).

Here, upscaling is primarily used to mean the development and application of techniques to predict, quantitatively or semi-quantitatively, the behaviour of large spatial regions based on observations made at much smaller scales. Typology is the development of environmental classifications or categories of data that can be related to local and regional observations in ways that permit inferences about areas in which local observations are lacking.

The typology approach consistently characterises functional data (essentially, the biogeochemical flux and budget information described in Chap. 3, Sect. 3.5.1) and information on the environmental context of the individual budget sites so that classification and upscaling of the functional information could be achieved. In this way, the information from the array of small, site-specific biogeochemical sites collected globally can be aggregated and, through developed typologies, used as proxies to ascribe coastal metabolic performance in low- or no-data coastal areas. Biogeochemical performance of coastal systems at regional and global scales can be inferred.

The objective of the typology approach was the identification of functionally-related coastal categories on the basis of relevant typology variables through the use of geospatial clustering with a software package (LOICZView) developed by the LOICZ Typology Group (*http://www.kgs.ukans.edu/Hexacoral/Envirodata/envirodata.html*). Consequently, the development of the typology approach has involved two primary elements: (*a*) a set of analytical and data management tools, mainly the geospatial clustering tools, and (*b*) a set of geo-referenced global environmental and biogeochemical databases. Internet access was provided to each element.

The geospatial clustering tool (LOICZView; *http://www.palantir.swarthmore.edu/loicz*) was developed to manipulate the typology datasets, with statistical and mapping capability to visualise results (see Text Box 1.6). This tool has been recently extended into a new platform, DISCO (*http://narya.engin.swarthmore.edu/disco*), which includes a fuzzy clustering routine and a time-series clustering capability.

Three typology datasets were developed for use in analysis and upscaling of the coastal zone biogeochemical flux assessments:

A global half-degree gridded environmental database (also referred to as the typology database), with the cells classified according to their relationship to the coastal zone. Some 259 200 half-degree cells describe Earth's surface and 47 057 of these cells have been identified as typology cells that describe the global coastal zone. Fig-

Text Box 1.6. Spatial clustering

Bruce Maxwell

When faced with a large amount of data, it can be difficult to extract meaningful information or discover structure within the data by simple observation. One quantitative procedure for extracting structure from data is spatial clustering, which groups similar data points and describes those groups using aggregate statistics such as means and standard deviations. The resulting set of extracted groups, or clusters, represents an abstraction of the original data that is simpler to manipulate and understand, while still retaining the relevant characteristics of the initial data.

One of the most widely applied algorithms for spatial clustering is the *K*-means algorithm (MacQueen 1967). The *K*-means algorithm falls into the category of unsupervised clustering algorithms, which means it begins with no prior knowledge of the characteristics of individual clusters in the data. In other words, the basic *K*-means algorithm requires only the number of clusters to be found, without any initial specification as to where the clusters might be.

The *K*-means algorithm is an iterative algorithm that starts by guessing where the clusters might be and then iteratively improves the guess until it converges to a stable answer (Fig. TB1.6.1). Given that we want to find *N* clusters in a dataset, the steps are as follows:

- Randomly select *N* data points as the initial cluster representatives $R_{1..N}$
- For each data point Xi, calculate the distance to each Rj using a distance measure *d*(Rj, Xi).
- Label each data point Xi as belonging to its closest cluster representative Rj.
- For each cluster representative Rj, calculate a new value for Rj by averaging the values of all data points belonging to that representative.
- Repeat the algorithm from step 2 until the cluster representatives $R_{1..N}$ do not change.

There are three primary issues when working with the *K*-means algorithm:

- How many clusters should there be?
- What distance measure is appropriate?
- Will the algorithm always converge to the same solution?

Of the three issues, the first is actually the most difficult to answer because it requires knowing the inherent structure of the data, which is what the method is trying to discern. Beyond simply making educated guesses, the general approach to answering this problem is to define a method of measuring the "goodness-of-fit" or "fitness measure" of a particular clustering of any given data. This measure should reflect the desire to have clusters that are compact within themselves and yet distant from other clusters. In a very practical sense, these measures often try to indicate how closely a clustering generated by a computer would match a clustering of the same data executed by a person. The optimal number of clusters should be the number that results in a clustering that maximises the measure of fitness.

Within the LOICZ typology group we have used Rissanen's minimum description length as a measure of fitness that balances the desire for compact clusters – which is generally achieved by having more clusters – with the desire for as few clusters as possible to maximise the benefits of clustering (Rissanen 1989). To discover a range of reasonable values for the number of clusters we test a range of clusterings and then graph the resulting fitness measure. This usually results in a small range of values that produce reasonable clusterings.

The second issue, distance measures, is dealt with in a separate part of the clustering software package. In short, the distance measure should reflect the user's understanding of similarity and should be appropriate to the data.

Finally, the answer to the third question is that the *K*-means algorithm will not always converge to the same answer. The algorithm is a "gradient descent" type algorithm, and it can get caught in local minima where the resulting cluster is stable but not optimal. To overcome this problem the user generally runs the algorithm multiple times from different starting points. The clustering that produces the least error in terms of the sum over all points of the distance to the nearest representative point is the result selected as the best answer. It is not uncommon for some datasets to be inherently unstable with respect to a small number of data points that do not really belong to any particular cluster. It is often the case, however, that these data points, upon further examination, are actually interesting and represent unique situations that are not well captured by a particular typology or classification.

Overall, the *K*-means clustering algorithm provides a useful tool for identifying structure in both small and large datasets. The key to producing useful results is to intelligently select the number of clusters and distance measure. The resulting clusters represent an abstraction of the data that may be more amenable to understanding and knowledge generation than the original compiled data.

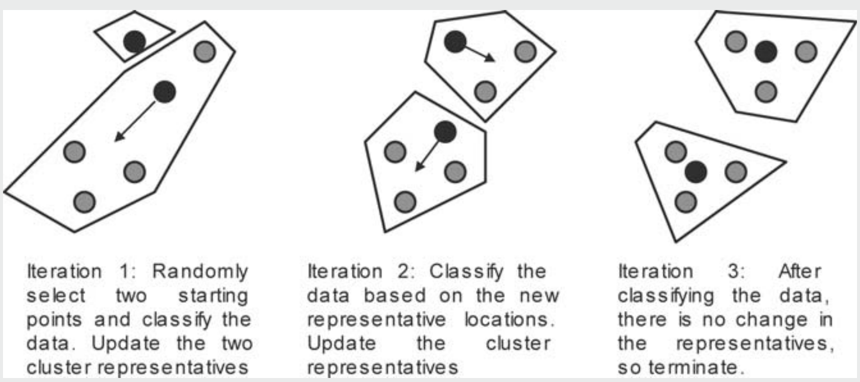


Fig. TB1.6.1. A simple example of the *K*-means clustering algorithm

ure 1.9 illustrates the grid system; the coastal zone is represented primarily by the coastal cells (containing actual shoreline), the Ocean I cells (~ one degree seaward of the coastline) and the terrestrial cells (~ one degree landward of the coastline). The remainder is classified as Ocean II (enclosed seas or basins), Ocean III, or In-

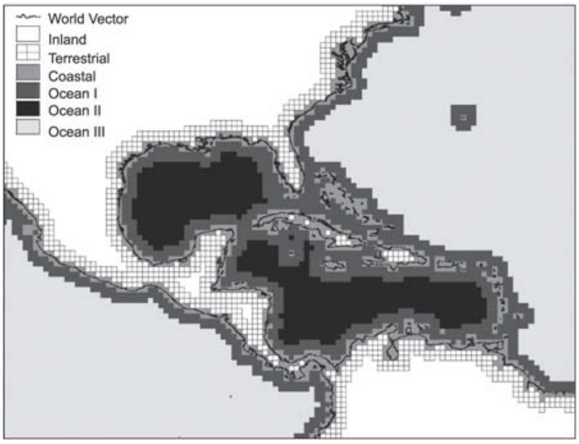


Fig. 1.9. Typology. Illustration of the scale and categories of the LOICZ half-degree grid cell definitions

Text Box 1.7. Area of grid cells vs latitude

Dennis P. Swaney and Robert W. Buddemeier

It is useful to remember that the cell area of any grid system based on latitude-longitude-coordinates on the globe has a strong latitudinal dependence (Figs. TB1.7.1, TB1.7.2).

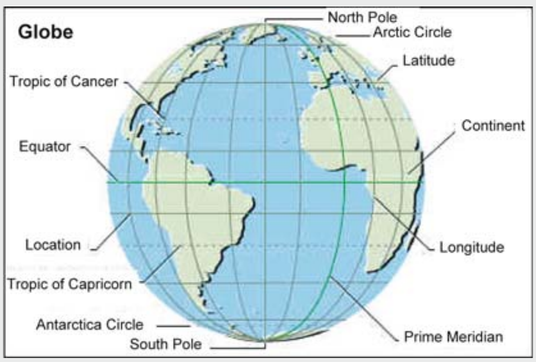


Fig. TB1.7.1. Latitude-longitude grid of the Earth. As latitude increases, the grid area decreases significantly because of narrowing of the longitudinal bands

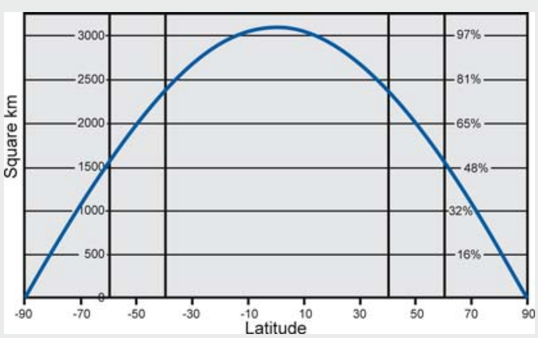


Fig. TB1.7.2. Relationship between latitude and the absolute area (km^2) of a half-degree (30' × 30') grid cell, and the area as a percentage of the grid cell area at the equator

land. This database contains a wide variety of public domain, global or near-global datasets, presented in a common grid format at 30' (half-degree) resolution (see Text Box 1.7). The variables represented are those that have relevance to either general coastal zone classification or to the factors believed likely to control or influence the fluxes of interest, including terrestrial, marine, coastal, atmospheric, human dimension, geomorphic and river-basin variables. The data for each variable has been georeferenced and scaled to the 30' cell array; a number of the variables have much finer resolution and all are accompanied by metadata descriptions. The native resolution of the data sets ranges from 1 km to several degrees. Where higher resolution data are aggregated into the half-degree cells, statistics on the sub-grid scale distributions are included in the database.

1. The biogeochemical budget database (also referred to as the budget database). The budget variables from the site and biogeochemical budget characteristics assembled by the LOICZ biogeochemical budgets activity (see Chap. 3, Sect. 3.2, Buddemeier et al. 2002, *http://data.ecology.su.se/mnode/*) include standardised nutrient load and flux data and calculations of nutrient sources and sinks (i.e., non-conservative fluxes) for more than 200 sites worldwide.
2. Km-scale basins: A database was derived from the HYDRO1k dataset (HYDRO1k Elevation Derivative Database, *http://edcdaac.usgs.gov/gtopo30/hydro*) using GIS to identify the drainage basins associated with the biogeochemical budget sites. The associated basin entries were populated with terrestrial, climatic, geomorphic and human variables by "clipping" GIS coverages of the parent datasets with the HYDRO1k basin coverage. This provided a more accurate and precise representations of those variables associated with the biogeochemical budget sites than can be obtained from the half-degree database. However, it did not address the issue of marine variables for which comparable data are not available.

The typology upscaling, for practical reasons, has evolved into two related processes. The km-scale river basin (catchment) data are used to identify relationships between terrestrial, hydrologic and human forcing functions and aspects of the biogeochemical fluxes that are or should be sensitive to those functions. This effort examined and compared relationships across a wide range of spatial scales, but did not in itself "upscale" by using measurements derived at one scale to characterise performance at another scale. The km-scale basin data were also used to compare the site-specific basin characteristics with characteristics inferred from the half-degree database alone. This comparison allowed determination of which budget characteristics, sites and environments were most amenable to upscaling with the existing datasets, and where (or whether) the additional effort involved in systematically developing coastal datasets based on km-scale budgets could be justified. The comparison also permitted assessment of the biases and uncertainties involved in upscaling.

The application of the typology approach to the global assessment of coastal metabolism is described in Chap. 3. In addition the work has yielded a number of related scientific products including a global pattern of nutrient loading (Smith et al. 2003). Importantly, the typology approach and tools have applications in a number of other assessment initiatives including the NOAA National Estuarine Eutrophication Assesssment Program in the United States and in coastal management assessments by National Institute of Water and Atmospheric Research (NIWA) in New Zealand. The NSF-sponsored project "Biogeography of the Hexacorallia" (a project of the US Ocean Biogeographic Information System, OBIS; *http://www.iobis.org*) has been a major collaborator, along with strong institutional support from Swarthmore University and the Kansas Geological Survey, as part of its major initiative in biogeoinformatics.

1.5.3 Socio-economic Evaluations

The importance of human activities in modifying the structure and function of the coastal zone was clearly recognised and incorporated into the strategic direction of LOICZ (Holligan and de Boois 1993). However, available socio-economic approaches and tools for assessment were few, especially for evaluating biogeochemical changes and for furthering "the scientific and socio-economic bases for the integrated management of the coastal environment" (a key LOICZ objective). Observational studies and modelling approaches were needed to provide an understanding of the external forcing effects of socio-economic changes (e.g., population growth, urbanisation) on material fluxes and to assess the human welfare impacts of flux changes.

LOICZ adopted and further developed several approaches to assess the drivers and consequences of societal pressures on coastal systems and the valuation of allied changes. The socio-economic initiatives were deliberately integrated into the biogeochemical activities rather than being developed as stand-alone initiatives.

The DPSIR framework (Turner et al. 1998, Turner and Salomons 1999; Fig. 1.6) provided a framework for identifying the key issues, questions and the spatial distribution of socio-economic activities and land uses, particularly for the assessment of drainage basin and linked coastal seas. The assessments derived from expert workshops provided the foundation for development and implementation of the LOICZBasins approach (see Sect. 1.5.4 below). River-basin studies in a number of the continental regions yielded observational and model-based socio-economic assessments involving both monetary valuations and multi-criteria assessments methods and techniques to identify practicable management options (see Chap. 4). In addition, products of socio-economic workshops and discussions in LOICZ, along with the direct involvement of sectoral expertise in other science projects, has led to a wider evaluation of human influences in studies directed at understanding biogeochemical fluxes, including the building of typology databases.

Effort was made to translate directly the largely observational information derived from the DPSIR framework into socio-economic input/output models that could be juxtaposed and linked to biogeochemical nutrient flux models. A major study across four sites in Southeast Asia, the SARCS-WOTRO-LOICZ project, yielded useful outcomes and, importantly, critically evaluated the methodology, identified limitations and uncertainties, and indicated useful modifications (Talaue-McManus et al. 2001). An improved understanding of the different scales (especially temporal) and richness of site data needed for model resolution was a vital result of the study.

The global valuation approach to ecosystem goods and services developed by Costanza et al. (1997) was explored. The evolution of ideas and methodologies being applied to this area of environmental economics was captured in a revised global valuation of ecological goods and services (Wilson et al. 2003).

1.5.4 River Basins – Material Fluxes and Human Pressures

The LOICZBasins approach involves regional assessment and synthesis of river catchment–coast interactions and human dimensions (Kremer et al. 2002). It addresses the impact of human society on material transport and catchment system changes, assessing their coastal impact, and aims to identify feasible management options, recognising the success and failure of past regulatory measures. Since the changes in fluxes are mostly land or river-catchment derived, each catchment–coastal sea system was treated as one unit – a water continuum.

Through standardised workshops, LOICZBasins provided a common framework for analysis, assessment and synthesis of coastal zone and management issues in most global regions. It comprised methodologies, common assessment protocols (qualitative and quantitative depending on data availability) and project designs for future work. LOICZBasins applied the DPSIR descriptive framework to determine the critical loads of selected substances discharging into the coastal seas, within diverse biophysical and socio-economic settings, under different development scenarios. The LOICZ Basins approach provided an expert typology of the current state and expected trends of coastal change in systems responding to land-based human forcing and natural influences.

Core actions for each regional workshop were:

a to identify and list key coastal change issues and related drivers in the catchment;
b to characterise and rank the various issues of change based on either qualitative information (i.e., expert judgement) or hard data from investigations or archived material, including identification of critical load and threshold information for system functioning; and
c to identify current or potential areas of impact ("hot spots") representing different types of pressures or changes in catchment-coast systems and to develop a relevant research proposal.

The following parameters were evaluated in each regional assessment:

- material flow of water, sediments, nutrients and priority substances (past, current and future trends);
- socio-economic drivers that have changed or will change the material flows;
- indicators for impacts on coastal zone functioning; and, where possible,
- a "critical load" for the coastal zone and "critical thresholds" for system functioning.

Assessment and ranking followed a sequence of scales allowing a full regional picture to be generated with the spatial scales increasing from local catchments, via subregional or provincial scales, up to regional scales, including country by country (in the case of large countries such as Brazil) or subcontinent.

For relatively data-rich Europe, the critical load and threshold concept developed within the United Nations Economic Commission for Europe's convention on Long-Range Transboundary Air was extended to the marine environment, and used for a cost-benefit analysis of management options. Critical loads provide key information for the development and application of indicators for monitoring. The indicators and targets were used to derive critical concentrations and, allowing for material transformations and dispersion in the coastal environment, a critical load to the coastal zone was calculated. This critical load, the critical outflow of the catchment, combined the inputs from socio-economic activities and transformations within the catchment. Scenarios for cost-benefit analysis and trade-offs were developed based on knowledge of the process links and the transformations of the material loads. Scenario-building was an integral part of this analysis.

A full assessment of all global regions has yet to be achieved. To date successful workshops have been held in Europe, Latin America, East Asia, Africa and Russia; the outcomes are presented in Chap. 4. In February 2001, the more detailed EuroCat research project (*http://www.iia-cnr.unical.it/EUROCAT/project.htm*) began with support from the EU; the findings discussed in Chap. 4 provide a case example which can be applied to other regions during LOICZ II (2003–12). Regional "Cat" projects are now underway in Africa, Latin America and East Asia.

1.5.5 Key Thematic Issues

In assessing global changes to the coastal zone, LOICZ has taken steps to assess and synthesise information about key thematic issues that influence and contribute to material fluxes being examined by core projects of the LOICZ program of activities. Specific thematic issues were addressed by specialist workshops, establishing collaborative international working groups and enlisting contributing projects from national and regional governments and agencies. The Contintental Margins Task Team, a working group jointly sponsored by LOICZ and the IGBP oceans project (Joint Global Oceans Flux Studies, JGOFS), evaluated the status and changes in materials and fluxes in the continental shelf margins (Lui et al. in press).

Collaboration with other scientific organisations on issues of common interest led to the establishment of co-sponsored working groups with the Scientific Committee on Oceanic Research (SCOR; *http://www.jhu.edu/scor*) to address: Coral reef responses to climate change: the role of adaptation; Working Group 104 (Buddemeier and Lasker 1999); and submarine groundwater discharge, Working Group 112 (Burnett et al. 2003). A LOICZ-sponsored working group addressed global changes in river delta systems (*http://www.deltasnetwork.nl*). The evolution of scientific understanding about trace gas emissions in the coastal zone and the measurement of sea-level changes were subjects of specialist review papers (Pacyna and Hov 2002, Goodwin et al. 2000). Expert international workshops to address thematic topics underpinned a number of LOICZ assessments e.g., sediment fluxes in catchments.

Contributed projects initiated by LOICZ-associated scientists have formed the basis of discussions at global LOICZ scientific conferences. The UK-based SURVAS (Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies; *http://www.survas.mdx.ac.uk*) and its offspring project DINAS-COAST (Dynamic and Interactive Vulnerability Assessment; *http://www.dinas-coast.net*) have contributed greatly to the establishment of common measurements and methodologies for assessing the vulnerability of coastal areas to the consequences of sea-level rise.

Integrated national studies were initiated by a number of countries to contribute to the LOICZ goals e.g., China, Japan, Portugal, the Netherlands, Russia, have added to the depth of regional assessments of coastal change. These were co-ordinated by national IGBP or LOICZ committees supported by national funding. Regional programs (e.g., EU ELOISE) have provided a strong basis for thematic and regional evaluations. International collaboration in coastal zone science and capacity-building in integrated coastal zone management (e.g., UNESCO's Intergovernmental Oceanographic Commission) has led to synergies in assessments and training in targeted regions (e.g., Africa) and in addressing thematic interests (e.g., the coastal module of the Global Ocean Observing System – GOOS).

1.6 Responses to Change

There are many responses by environmental management and policy-makers to the changing pressures and status of the coastal zone, with varying levels of success (GESAMP 1996, Cicin-Sain and Knecht 1998, von Bodungen and Turner 2001, Olsen 2003). In some cases, initiatives were already developed or in place prior to the first Earth Summit (United Nations Conference on Environmental Development, UNCED) held in Rio de Janeiro in 1992; in others, efforts have been developed in response to the Rio Conference and the World Summit on Sustainable Development in Johannesburg, 2002. However, the wheels grind slowly in governments and in major international agencies, particularly to fit consultative and funding cycles, and thus the advent of a number of programs to address key issues is only now becoming apparent. The increase in local and sometimes wider participatory management approaches based on local communities is a noteworthy advance during the last decade, as environmental awareness and knowledge in many coastal communities and national populaces have improved.

There are major efforts in the global scientific assessment of the coastal zone to determine the pressures, state and impacts on the systems in order to provide a basis for building management approaches and policy actions. The IGBP program has completed its first 10-year assessment of global change (Steffen et al. 2002, 2004). The Intergovernmental Oceanographic Commission of UNESCO in 1995–6 moved to embrace the "brown waters" of the coastal seas and has initiated a number of actions including the Global Ocean Observing System (GOOS, *http://ioc.unesco.org/goos*). The Global Coral Reef Monitoring Network has been established (*http://www.gcrmn.org*). The UNEP Regional Seas program, FAO programmes and GESAMP continue with vital initiatives. Through the GEF (Global Environment Facility) and within the framework of UNEP (United Nation Environmental Programme), large-scale programmes have been launched to monitor Large Marine Ecosystems (LME) and to strengthen the development of governance in the management process in these LMEs (*http://www.edc.uri.edu/lme*). A global water programme, GIWA (Global International Waters Assessment; *http://www.giwa.org*), is being led by UNEP with financial participation of various international organisations to assess the environmental conditions and problems of water. The Millennium Ecosystem Assessment, begun in 2001, aims to provide a global environmental assessment to underpin various international Conventions (Biological Diversity, Combat of Desertification, Wetlands) and to provide information for policy and decision-making. Regional policy directives relate to and underpin coastal zone management and assessment. These include the European Union's Water Framework Directive announced by the European Union in November 2000, the European Commission's communication to the European Parliament on a proposal for a coherent strategy for coastal zone management, and HELCOM and OSPAR for the Baltic and North Atlantic Seas.

Global assessments in programmes run by intergovernmental organisations and non-governmental organisations (WRI 2000, Millennium Ecosystem Assessment, *http://www.millenniumassessment.org*) involving structured regional scientific networks are helping make inroads into the problems of mapping and determining the extent and status of key coastal habitats. For example, the UNEP-World Conservation Monitoring Centre (*http://www.unep-wcmc.org*) continues mapping assessments for coral reef, mangrove and seagrasses atlases; the Intergovernmental Oceanographic Commission of UNESCO (IOC) coordinates a global network actively monitoring coral reef changes (Wilkinson 2000).

Ecological considerations show that the coastal zone comprises evolving ecosystems and that the variability of natural conditions is due to factors ranging from the local to the global, including human and non-human effects. Current and developing research programmes, despite clear signs of being more focused on socio-economic issues, still remain remote from the wider public. Education is clearly the main instrument to promote dialogue and help bring research results into practical application. Such an approach should not be based on just an analysis of direct causes for concern but should result from the consideration of the convergence and interrelationships between science and a multifaceted society (Ducrotoy 2002). The global perspective offered in this book should help in linking elements that form the coastal system in a holistic context, providing a large-scale interpretation of biogeochemical processes that can contribute to management, policy and community education.

References

Aguirre-Munoz A, Buddemeier RW, Camacho-Ibar V, Carriquiry JD, Ibarra-Obando SE, Masset BW, Smith SV, Wulff F (2001) Sustainability of coastal resource use in San Quintin, Mexico. Ambio 30(3):142–149
Allanson BR, Baird D (eds) (1999) Estuaries of South Africa. Cambridge University Press, UK
Alongi DM (1999) Coastal ecosystem processes. CRC Press, Florida
Arthurton RS (1998) Marine-related physical natural hazards affecting coastal megacities of the Asia-Pacific region – awareness and mitigation. Ocean & Coastal Management 40:65–85
Awosika L (1999) Sub-Sahara Africa coastal zone: assessment of natural and human-induced changes (Abstract). In: Report of the LOICZ Open Science Meeting 1999: Regimes of Coastal Change. LOICZ IPO, Texel, The Netherlands, pp 25–26
Baird D (1998) Orientors and ecosystem properties in coastal zones. In: Muller F, Leupelt M (eds) Ecotargets, goal functions and orientors. Springer-Verlag, Berlin Heidelberg, pp 232–242
Baird D (1999) Estuaries as ecosystems: a functional and comparative analysis. In: Allanson BR, Baird D (eds) Estuaries of South Africa. Cambridge University Press, UK, pp 269–288
Baird D, Heymans JJ (1996) Assessment of ecosystem changes in response to freshwater inflow of the Kromme River estuary, St Francis Bay, South Africa: a network analysis approach. Water SA 22(4):307–318
Baird D, Ulanowicz RE (1989) The seasonal dynamics of the Chesapeake Bay ecosystem. Ecological Monographs 59:329–364
Baird D, Ulanowicz RE (1993) Comparative study on the trophic structure, cycling and ecosystem properties of four tidal estuaries. Marine Ecology Progress Series 99:221–237
Baird D, McGlade JM, Ulanowicz RE (1991) The comparative ecology of six marine ecosystems. Philosophical Transactions of the Royal Society London Series B 333:15–29
Baird D, Ulanowicz RE, Boynton WR (1995) Seasonal nitrogen dynamics in the Chesapeake Bay. Estuarine and Coastal Shelf Science 41:137–162
Baird D, Luczkovich J, Christian RR (1998) Assessment of spatial and temporal variability in ecosystem attributes of the St Marks National Wildlife Refuge, Apalachee Bay, Florida. Estuarine and Coastal Shelf Science 47:329–349
Barnes DJ, Taylor RB (2001) On the nature of skeletal density banding in scleractinian corals: fine banding and seasonal patterns. Journal of Experimental Marine Biology and Ecology 126:119–134
Beaugrand D, Reid PC, Ibanez F (2002) Reorganisation of North Atlantic marine copepod biodiversity and climate. Science 296: 1692–1694
Bennett EM, Carpenter SR, Caraco NF (2001) Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51(3):227–234
Behrendt H, Kornmilch M, Opitz D, Schmoll O Scholz G (2002) Estimation of the nutrient inputs into river systems – experiences from German rivers. Regional Environmental Change 3:107–117
Bergman MJN, Lindeboom HJ (1999) Natural variability and the effects of fisheries in the North Sea: towards an integrated fisheries and ecosystem management? In: Gray JS (ed) Biogeochemical cycling and sediment ecology. Kluwer, Dordrecht, pp 173–184
Beukema JJ, Essink K Michaelis H (1996) The geographic scale of synchronized fluctuation patterns in zoobenthos populations as a key to underlying factors: climatic or man-induced. ICES Journal of Marine Science 53:964–971
Black KD, Shimmield GB (eds) (2003) Biogeochemistry of marine systems. Blackwell Publishing, UK
Bouwman AF, van der Hoek KW, Olivier JGJ (1995) Uncertainties in the global sources distribution of nitrous oxide. Journal of Geophysical Research 100:2785–2800
Bradley RS (2002) Climate change – past, present and future: a personal perspective. In: Steffen W, Jager J, Carson DJ, Bradshaw C (eds) Challenges of a changing Earth: Proceedings of the Global Change Open Science Conference Amsterdam, The Netherlands 10–13 July 2001. Springer-Verlag, Berlin Heidelberg, pp 109–112
Broeker WS (1991) The great ocean conveyer. Oceanography 4:79–89
Broeker WS (1994) An unstable superconveyor. Nature 367:414–415
Buddemeier RW, Lasker HR (1999) Coral reefs and environmental change – adaptation, acclimation or extinction. American Zoologist 39(1)
Buddemeier RW, Smith SV, Swaney DP, Crossland CJ (eds) (2002) The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No. 24
Buddemeier RW, Kleypas JA, Aronson RB (2004) Coral reefs and global climate change. Potential contributions of climate change to stresses on coral reef ecosystems. Pew Centre of Global Climate Change, USA
Burbridge PR (1999) The challenge of demonstrating socio-economic benefits of integrated coastal management. In: Salomons W, Turner RK, de Lacerda LD, Ramachandran S (eds) Perspectives on integrated coastal zone management. Springer, Berlin, Heidelberg, pp 35–53
Burke LK, Yumiko K, Kassem K, Revenga C, Spalding M, McAllister D (2001) Pilot analysis of global ecosystems: coastal ecosystems. World Resources Institute, Washington DC
Burnett WC, Chanton JP, Kontar E (2003) Submarine groundwater discharge. Biogeochemistry Special Issue 66(1–2)
Busalacchi AJ (2002) The coupled climate system: variability and predictability. In: Steffen W, Jager J, Carson DJ, Bradshaw C (eds) Challenges of a changing Earth: proceedings of the global change open science conference Amsterdam, The Netherlands 10–13 July 2001. Springer-Verlag, Berlin Heidelberg, pp 117–120
Christensen V (1995) Ecosystem maturity – towards quantification. Ecological Modelling 77:3–32
Christian R, Fores E, Comin F, Varioli O, Naldi M, Ferrari I (1996) Nitrogen cycling networks of coastal waters: influence of trophic status and primary producer form. Ecological Modelling 87: 111–129
Cicin-Sain B, Knecht RW (1998) Integrated coastal and ocean management. Concepts and practices. Island Press, Washington DC
Conley DJ, Schelske CL, Stoermer EF (1993) Modification of the biogeochemical cycle of silica with eutrophication. Marine Ecology Progress Series 101:179–192
Cook PJ (1996) Societal trends and their impacts on the coastal zone and adjacent seas. British Geological Survey Technical Report WQ/96/3
Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M. (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260
Crossland CJ (2000) Improved strategies for linking coastal science and users. In: Pacyna JM, Kremer HH, Pirrone N, Barthel K-G (eds) Socio-economic aspects of fluxes of chemicals into the marine environment – workshop report, Keller, Norway 8–10 March 1999. EURO 19089. European Commission, Luxembourg pp 199–210
Crossland CJ, Kenchington RA (2001) The Great Barrier Reef, Australia: partnerships for wise use. In: von Bodungen B, Turner RK (eds) Science and integrated coastal management. Dahlem University Press, Berlin, pp 135–148
Daily GC (1997) Nature's services: societal dependence on natural ecosystems. Island Press, Washington DC
Daily GC, Walker G (2000) Seeking the great transition. Nature 403: 243–245
de Groot R, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41:393–408
de Vries I (2001) Shoreline and land-use development perspectives in the context of long-term decreasing functional diversity in the delta region, SW Netherlands. In: von Bodungen B, Turner RK (eds) Science and integrated coastal management. Dahlem University Press, Berlin pp 113–120
Ducrotoy J-P (1999) Protection, conservation and biological diversity in the North-east Atlantic. Aquatic Conservation: Marine and Freshwater Ecosystems 9:313–325
Ducrotoy J-P (2002) Education challenges in the North Sea area. Marine Pollution Bulletin 47:246–252

Ducrotoy J-P, Elliot M (1997) Interrelations between science and policy-making: the North Sea example. Marine Pollution Bulletin 34(9):686–701
Ducrotoy J-P, Pullen S (1999) Integrated coastal zone management commitments and developments from an international, European and United Kingdom perspective. Ocean and Coastal Management 42:1–18
Ducrotoy J-P, Elliot M, Dejong V (2000). The North Sea. In: Sheppard CRC (ed) Seas at the Millennium. Elsevier, London.
Faber M, Petersen T, Schiller J (2002) Homo oeconomicus and homo politicus in ecological economics. Ecological Economics 40(3): 323–333
FAO (1999) The state of world fisheries and aquaculture. FAO, Rome
Fasham MJR (ed) (2003) Ocean biochemistry: a synthesis of the Joint Global Ocean Flux Study (JGOFS). Global change the IGBP series. Springer-Verlag, Berlin, Heidelberg
Field JG, Moloney CL, Atwood CG (1989) Network analysis of simulated succession after an upwelling event. In: Wulff F, Field JG, Mann KH (eds) Network analysis in marine ecology: methods and application. Coastal and Estuarine Studies 32, Springer-Verlag, Heidelberg, pp 132–158
Field JG, Hempel G, Summerhayes CP (2002) Oceans 2020. Science, trends and the challenge of sustainability. Island Press, Washington DC
Fores E, Christian RR (1993) Network analysis and nitrogen cycling in temperate, wetland ricefields. Oikos 67:299–308
Frankignoulle M (2000) Biogas transfer in estuaries. The BIOGEST project report to the EU. Liege, Belgium.
Gaedke U, Straile D (1994) Seasonal changes of trophic transfer efficiencies in a plankton foodweb derived from biomass size distribution and network analysis. Ecological Modelling 75/76: 435–445
GESAMP (1996) The contributions of science to coastal zone management. GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Reports and Studies. FAO, Rome, No. 61
GESAMP (2001). A sea of troubles. GESAMP (IMO/FAO/UNESCO/IOC/WMO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Reports and Studies. FAO, Rome, No. 70, p 35 and No. 71
Gislason H (1994) Ecosystem affects of fishing activities in the North Sea. Marine Pollution Bulletin 29:520-527
Glavovic B (2000) Our coast, our future: a new approach to coastal management in South Africa. Department of Environmental Affairs & Tourism, South Africa
Goodwin I, Harvey N, van de Plassche O, Oldfield, F (2000). Research targets. 2000 years of climate-induced sea level fluctuations. EOS Transactions of the American Geophysical Union 81(28):311–314
Gordon DC Jr., Boudreau PR, Mann KH, Ong J-E, Silvert WL, Smith SV, Wattayakorn G, Wulff F, Yanagi T (1996) LOICZ biogeochemical modelling guidelines. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 5
Grainger RJR, Garcia SM (1996) Chronicles of marine fishery landings (1950–1994): trend analysis and fisheries potential. FAO Fisheries Technical Paper 359. FAO, Rome
Gren I-M, Turner RK, Wulff F (2000) Managing a sea – the ecological economics of the Baltic. Earthscan Publications, UK
Guinotte JM, Buddemeier RW, Kleypas JA (2003) Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22(4):551–558
Harvey N, Caton B (2003) Coastal management in Australia. Oxford University Press, Melbourne, Australia
Hayes MO (1964) Lognormal distribution of inner continental shelf widths and slopes. Deep-Sea Research 11(1):53–78
Hinrichsen D (1998) Coastal waters of the world: trends, threats and strategies. Island Press, Washington DC
Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Marine and Freshwater Research 50:839–866
Holligan PM, de Boois H (eds) (1993) Land-Ocean Interactions in the Coastal Zone (LOICZ) – science plan. IGBP global change report. International Geosphere-Biosphere Programme, Stockholm, No. 25
Holligan PM, Reiners WA (1991) Predicting the responses of the coastal zone to global change. Advances in Ecological Research 22:211–255
Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001) Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, New York
Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Loogh JM, Marshall P, Nystrom M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human impacts and the resilience of coral reefs. Science 301(5635):929–933
Humborg C, Conley DJ, Rahm L, Wulff F, Cociasu A, Ittekkot V (2000) Silicon retention in river basins: far-reaching effects on biogeochemistry and aquatic food webs in coastal marine environments. Ambio 29(1):45–50
Huntley D, Leeks G, Walling D (eds) (2001) Land ocean interaction, measuring and modelling fluxes from river basins to coastal seas. IWA Publishing, UK
Ibanez F, Ducrotoy J-P (2002) Ecological groups of estuarine macrobenthic invertebrates: changes in space and time. Journal of the Marine Biological Association UK 82(5):749–769
Ittekkot V, Humborg C, Schafer P (2000) Hydrological alterations and marine biogeochemistry: a silicate issue? BioScience 50(9):776–782
Jennings S, Kaiser MJ (1998) The effects of fishing on marine ecosystems. Advances in Marine Biology 34:201–352
Jickells TD (1998) Nutrient biogeochemistry of the coastal zone. Science 281:217–222
Jickells TD, Boesch DF, Colijn F, Elmgren R, Frykblom P, Mee LD, Pacyna JM, Voss M, Wulff FV (2001) Group report: transboundary issues. In: von Bodungen B, Turner RK (eds) Science and integrated coastal management. Dahlem University Press, Berlin pp 93–112
Kaiser MJ, de Groot SJ (2000) The effects of fishing on non-target species and habitats. Blackwell Science, UK
Kaiser MJ, Spencer BE (1996) The behavioural response of scavengers to beam trawling. ICES, CM/B5
Kelleher G (1995) Case study 2. The Great Barrier Reef, Australia. In: The Contributions of Science to Coastal Zone Management, GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Reports and Studies. FAO, Rome, No. 61, pp 31–44
Klein RJT, Nicholls RJ, Thomalla F (2003). The resilience of coastal megacities to weather-related hazards: a review. Report to the Disaster Management Facility, World Bank, September 2002
Kleypas JA, Buddemeier RW, Archer D, Gattuso J-P, Langdon C, Opdyke BN (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science 284:118–120
Kremer HH, Salomons W and Crossland CJ (2002) Human dimensions of land-based fluxes to the coastal zone: the LOICZBasins approach. In: de Lacerda LD, Kremer HH, Kferve B, Salomons W, Marshall Crossland JI and Crossland CJ (eds) South American ba-sins: LOICZ global change assessment and synthesis of river catchment-coastal sea interactions and human dimensions. LOICZ Reports and Series, LOICZ, Texel, The Netherlands, No. 21, pp 61–72
Kroeze C, Seitzinger SP, Domingues R (2001) Future trends in worldwide river nitrogen transport and related nitrous oxide emissions: a scenario analysis. In: Optimizing nitrogen management in food and energy production and environmental protection: Proceedings 2nd International Nitrogen Conference on Science and Policy. The Scientific World, vol 1
Lakhan VC (2003) Advances in marine modeling. Elsevier Oceanography Series Elsevier, The Netherlands, vol 67
Ledoux L, Turner RK (2002) Valuing ocean and coastal resources: a review of practical examples and issues for further action. Ocean and Coastal Management 45:583–616
Lindeboom HJ (2000) The need for closed areas as conservation tools. In: Kaiser MJ, de Groot SJ (eds) Effects of fishing on non-target species and habitats. Blackwell Science UK, pp 290–302
Lindeboom HJ (2002a) Changes in coastal zone ecosystems. In: Wefer G, Berger H, Behre K-E, Jansen E (eds) Climate development and history of the North Atlantic realm. Springer, Berlin, pp 447–455

Lindeboom HJ (2002b) The coastal zone: an ecosystem under pressure. In: Field JG, Hempel G, Summerhayes CP (eds) Oceans 2020. Science, trends and the challenge of sustainability. Island Press, Washington DC, pp 51–86

Lindeboom HJ (in press). Comparison of effects of fishing with effects of natural events and non-fishing anthropogenic impacts on benthic habitats. In: Barnes PW, Thomas JP (eds) Benthic habitats and the effects of fishing. American Fish Society Symposium 41, Bethesda, Maryland

Lui KK, Atkinson L, Quiñones R, Talaue-McManus, L (eds) (in prep) Carbon and nutrient fluxes in continental margins: a global synthesis. Global change – the IGBP series. Sringer Verlag, Berlin

MacQueen J (1967) Some methods for classification and analysis of multivariate observations. Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, vol 1, pp 281–297

Mandelbrot BB (1967) How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science 156:636–638

Mann KH, Lazier JRN (1996) Dynamics of marine systems, 2nd edn. Blackwell, Oxford

Matthews E, Payne R, Rohweder M, Murray S (2000) Pilot analysis of global ecosystems: forest ecosystems. World Resources Institute, Washington DC

McManus JL, Menez AB, Reyes K, Vergara S, Ablan M (2000) Coral reef fishing and coral-algal phase shifts: implications for global reef status. ICES Journal of Marine Science 57(3):572–578

Meybeck M (1998) Man and river interface: multiple impacts on water and particulates chemistry illustrated in the Seine river basin. Hydrobiologia 373/374:1–20

Milliman JD (1997) Blessed dams or dammed dams. Nature 386: 325–327

Molenaar FJ, Breeman AM (1997)Latitudinal trends in the growth and reproductive seasonality of *Delessaria sanguinea, Membranoptera alata*, and *Phycodrys rubens* (Rhodophyta). Journal of Phycology 33(3):330–343

Moore B (2002) Challenges of a changing Earth. In: Steffen W, Jager J, Carson DJ, Bradshaw C (eds) Challenges of a changing Earth: proceedings of the global change open science conference Amsterdam, The Netherlands 10–13 July 2001. Springer-Verlag, Berlin Heidelberg, pp 7–17

Moscardo G (1997) Sustainable tourism and the environment. In: Gee CY (ed) International tourism: a global perspective. World Tourism Organisation, Madrid, pp 253–276

Munn RE, Whyte A, Timmermann P (2000) Emerging environmental issues for the 21st century: a study for GEO-2000. SCOPE and UNEP, Nairobi

Neal C, House WA, Whitton BA, Leeks GJL (1998). Water quality and biology of UK rivers entering the North Sea: the land ocean interaction study (LOIS) and associated work. Science of the Total Environment 210/211:1–609

Nicholls RJ, Small C (2002) Improved estimates of coastal population and exposure to hazards released. EOS Transactions of the American Geophysical Union 83(28):301–305

Nixon SW (2003) Replacing the Nile: are anthropogenic nutrients providing the fertility once brought to the Mediterranean by a great river? Ambio 32(1):30–39

NRC (2002) Oil in the sea III: sources, fates and effects. National Research Council Committee on Oil in the Sea. National Academy Press, Washington DC

OECD (2001) A new strategy for the environment. OECD Observer, Policy Brief July 2000

Olsen SB (ed) (2003) Crafting coastal governance in a changing world. Coastal Management Report No. 2241, Coastal Resources Centre, University of Rhode Island USA

Pacyna JM, Hov O (2002) Sea to air transport of trace gases in the coastal zone: a literature review. Regional Environmental Change 2:185–200

Pauly D, Maclean J (2003) In a perfect ocean. Island Press, Washington DC

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F (1998) Fishing down marine food webs. Science 279: 860–863

Pearce PL (1997) Tourism market segments and travel psychology. In: Gee CY (ed) International tourism: a global perspective. World Tourism Organisation, Madrid, pp 137–156

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chapellaz J, Davis M, Delaygue M, Kotlyakov VM, Legrand M, Lippenkov VY, Lorius C, Pepin L, Ritz C, Saltman E, Stievenard M (1999) Climate and atmospheric history over the past 420 000 years from the Vostok ice core, Antarctica. Nature 399:436–439

Pernetta JC, Milliman JD (1995) Land-Ocean Interactions in the Coastal Zone – implementation plan. IGBP global change report. International Geosphere-Biosphere Programme, Stockholm, No. 33

Pethick J (2001) The Anglian coast. In: von Bodungen B, Turner RK (eds) Science and integrated coastal management. Dahlem University Press, Berlin, pp 121–134

Pike J, Kemp AES (1997) Early Holocene decadal-scale ocean variability recorded in Gulf of California laminated sediments. Paleoceanography 12:227–238

Piraino S, Fanelli G, Boero F (2002) Variability of species' roles in marine communities: change of paradigms for conservation priorities. Marine Biology 140 (5):1067–1074

Rabelais NN, Turner RE, Justic D, Dortch Q, Wiseman WJ, Sen Gupta BK (1996) Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19(2B): 386–407

Rabelais NN, Turner RE, Dortch Q, Justic D, Bierman VJ, Wiseman WJ (2002) Nutrient-enhanced productivity in the northern Gulf of Mexico: past, present and future. Hydrobiologia 475/476:39–63

Redfield AC, Ketchum BH, Richards FA (1963) The influence of organisms on the composition of sea-water. In: Hill MN (ed) The Sea, vol 2, pp 26–77

Reid PC, Edwards M, Hunt HG (1998) Phytoplankton change in the North Atlantic. Nature 391:546–548

Rial JA (2004) Abrupt climate change: chaos and order at orbital and millennial scales. Global and Planetary Change 41:95–109

Richardson K, Jorgensen BB (1996) Eutrophication: definition, history and effects. Eutrophication in coastal marine ecosystems. Coastal and Estuarine Studies 53:1–19

Rissanen J (1989) Stochastic complexity in statistical inquiry. World Scientific Publishing Co., Singapore

Sainsbury KJ, Campbell RA, Lindholm R, Whitelaw AW (1997) Experimental management of an Australian multi-species trawl fishery: examining the possibility of trawl-induced habitat modification. In: Pikitch EL, Huppert DD, Sissenwine MP (eds) Global trends: fisheries management. Proceedings of the American Fish Society Symposium 20:102–112

Sala OE, Jackson RB, Mooney HA, Howarth RW (2000) Methods in ecosystem science. Springer, New York

Salomons W (2004) European catchments: catchment changes and their impact on the coast. Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

Salomons W, Turner RK, Lacerda LD, Ramachandran S (1999) Perspectives on integrated coastal zone management. Springer-Verlag, Berlin Heidelberg

San Diego-McGlone MLS, Smith SV, Nicholas VF (2000) Stoichiometric interpretations of C:N:P ratios in organic waste materials. Marine Pollution Bulletin 40:325-330

Scialabba N (1998) Integrated coastal area management and agriculture, forestry and fisheries. FAO guidelines. Environment and Natural Resources Service, FAO, Rome

Seuront L, Gentilhomme V, Lagadeuc Y (2002) Small-scale patches in tidally mixed coastal waters. Marine Ecology Progress Series 232:16–44

Sheppard CRC (2002) Seas at the millennium. Elsevier, London

Shi H, Singh A (2003) Status and interconnections of selected environmental issues in the global coastal zones. Ambio 32(2):145–152

Smith SV (2002) Carbon-nitrogen-phosphorus fluxes in the coastal zone: the global approach. IGBP Global Change Newsletter 49: 7–11

Smith RD, Maltby E (2003) Using the ecosystem approach to implement the convention on biological diversity: key issues and case studies. IUCN, Gland, Switzerland and Cambridge, UK

Smith SV, Renwick WH, Buddemeier RW, Crossland CJ (2001) Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15(3):697–707

Smith SV, Swaney DP, Talaue-McManus L, Bartley JD, Sandhei PT, McLaughlin CJ, Dupra VC, Crossland CJ, Buddemeier RW, Maxwell BA, Wulff F (2003) Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. BioScience 53:235–245

SOER (2002) Australia State of the environment. Environment Australia, Canberra

Steffen W, Jager J, Carson DJ, Bradshaw C (eds) (2002) Challenges of a changing Earth: proceedings of the global change open science conference Amsterdam, The Netherlands 10–13 July 2001. Springer-Verlag, Berlin Heidelberg

Steffen W, Sanderson A, Tyson P, Jager J, Matson P, Moore III B, Oldfield F, Richardson K, Schellnhuber H-J, Turner BLII, Wasson R (2004) Global change and the Earth system: a planet under pressure. IGBP Global Change Series. Springer-Verlag, Berlin Heidelberg

Summerhayes CP, Lochte K (2002) Ocean studies for offshore industry. In: Field JG, Hempel G, Summerhayes CP (2002) Oceans 2020. Science, trends and the challenge of sustainability. Island Press, Washington DC, pp 137–162

Sverdrup HU, Johnson MW, Fleming RH (1942) The oceans. Prentice-Hall, New York

Swaney DP, Savchuk O, Humborg C (in prep) A comparative biogeochemical analysis of five coastal Baltic ecosystems

Sylvand B, Ducrotoy J-P (1998) Monitoring coastal and estuarine systems: the need for an integrated approach. In: Falkenmark M (ed) With rivers to the sea: interactions and land activities, fresh water and enclosed coastal sea. Stockholm International Water Institute, Stockholm, pp 189–204

Szmant AM (ed) (2001) Community dynamics of coral reef algae. Coral Reefs Special Issue 19(4): 299–425

Talaue-McManus L (2002) Global change in the coastal zone: the case of Southeast Asia. In: Steffen W, Jager J, Carson DJ, Bradshaw C (eds) Challenges of a changing Earth: proceedings of the global change open science conference Amsterdam, The Netherlands 10–13 July 2001. Springer-Verlag, Berlin Heidelberg, pp 101–105

Talaue-McManus LT, Kremer HH and Marshall-Crossland JI (2001) Biogeochemical and human dimensions of coastal functioning and change in Southeast Asia. Final report of the SARCS/WOTRO/LOICZ project 1996–1999. LOICZ Reports and Studies. LOICZ IPO, Texel, The Netherlands, No. 17

Talaue-McManus LT, Smith SV, Buddemeier RW (2003) Biophysical and socio-economic assessments of the coastal zone: the LOICZ approach. Ocean and Coastal Management 46:323–333

Turner RK (2000) Integrating natural and socio-economic science in coastal management. Journal of Marine Systems 25:447–460

Turner RK, Salomons W (1999) Coastal management principles and practice; introduction and overview. In: Salomons W, Turner RK, de Lacerda LD, Ramachandran S (eds) Perspectives on integrated coastal zone management. Springer-Verlag, Berlin Heidelberg, pp 1–10

Turner RE, Qureshi N, Rabelais NN, Dortch Q, Justic D, Shaw RF, Cope J (1998a) Fluctuating silicate:nitrate ratios and coastal plankton food webs. Proceedings National Academy of Science, USA 95:13048–13051

Turner RK, Adger WN, Lorenzoni I (1998b) Towards integrated modelling and analysis in coastal zones: principles and practice. LOICZ Reports and Studies. LOICZ IPO, Texel, The Netherlands, No. 11

Tyson P, Steffen W, Mitra AF, Fu C, Lebel L (2001) The earth system: regional-global linkages. Regional Environmental Change 2:128–140

UNEP (1995) Water quality of world river basins. UNEP, Nairobi

UNEP (2002) North America's environment: a thirty-year state of environment and policy retrospective. UNEP, New York

UNESCO (2003) The integrated strategic design plan for the coastal ocean observations module of the Global Ocean Observing System. GOOS Report No. 125, IOC Information Documents Series No. 1183, UNESCO

van Drecht G, Bouwman AF, Knoop JM, Meinardi C, Beusen A (2001) Global pollution of surface waters from point and nonpoint sources of nitrogen. In: Optimizing nitrogen management in food and energy production and environmental protection: Proceedings 2nd International Nitrogen Conference on Science and Policy. The Scientific World, vol 1(S2):632–641

Vitousek PM, Mooney HA, Lubchenco J, Melilli JM (1997) Human domination of Earth's ecosystems. Science 227:494–499

Voinov A, Costanza R, Wainger L, Boumans R, Villa F, Maxwell T, Voinov H (1999) Patuxent landscape model: integrated ecological economic modeling of a watershed. Environmental Modelling & Software 14:473–491

von Bodungen B, Turner RK (eds) (2001) Science and integrated coastal management. Report of the 85th Dahlem Workshop Berlin December 12–17 1999. Dahlem University Press, Berlin

von Storch H, Reinhardt DT (1997) Scenario of storm surge statistics for the German Bight at expected time of double atmospheric carbon dioxide concentration. Journal of Climate 10: 2653–2662

Wakenfeld DR, Oliver JK, Morrissey JI (eds) (1998) State of the Great Barrier Reef World Heritage Area. Great Barrier Reef Marine Park Authority, Townsville

Walker PA (1998) Fleeting images: dynamics of North Sea ray populations. PhD thesis, University of Amsterdam

Walther G-R, Post W, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395

Warner AJ, Hays GC (1994) Sampling by the continuous plankton recorder survey. Progress in Oceanography 334:237–256

Warwick RM (1989) The role of meiofaun in the marine ecosystem – evolutionary considerations. Zoological Journal of the Linnean Society London 96(3):229–241

Watson RT, Zinyowera MC, Moss RH, Dokken DJ (1997) The regional impacts of climate change: an assessments of vulnerability. Cambridge University Press, UK

Wilkinson C (2000) Status of coral reefs of the world: 2000. Global coral reef monitoring network. Australian Institute of Marine Science, Townsville

Wilkinson C, Linen O, Ceasar H, Hodgson G, Rubens J, Strong AE (1999) Ecological and socio-economic impacts of the 1998 coral mortality in the Indian Ocean: an ENSO impact and warning of future change. Ambio 28:188–196

Wilson MA, Costanza R, Boumans R, Liu S (2003) Integrating assessment and valuation of ecosystem goods and services provided by coastal systems. In Wilson JG (ed) The intertidal ecosystem. Royal Irish Academy, Dublin, pp 1–28

Witbaard R (1996) Growth variations in *Arctica islandica* L. (Mollusca): a reflection of hydrography related food supply. ICES Journal of Marine Science 53:981–987

Wolanski E (ed) (2001) Oceanographic processes of coral reefs: physical and biological links in the Great Barrier Reef. CRC Press, Florida

Wood S, Sebastian K, Scherr SJ (2000) Pilot analysis of global systems: agrosystems. International Food Policy Research Institute and World Resources Institute, Washington DC

WRI (2000) World resources 2000–2001. People and ecosystems. The fraying web of life. World Resources Institute, Washington DC

WTTC (2003) Blueprint for new tourism. World Travel & Tourism Council, *www.wttc.org*

Wulff F, Field JG, Mann KH (eds) (1989) Network analysis in marine ecology – methods and applications. Coastal and Estuarine Studies No. 32. Springer-Verlag, Berlin Heidelberg

Wulff F, Rahm L, Larsson P (2001) A systems analysis of the Baltic Sea. Ecological Studies, Springer-Verlag, Berlin Heidelberg, No. 148

Chapter 2

Dynamics of the Coastal Zone

James P. M. Syvitski, Nick Harvey, Eric Wolanski, William C. Burnett, Gerardo M. E. Perillo, Vivien Gornitz
Contributors: *Russell K. Arthurton, Henry Bokuniewicz, Janet W. Campbell, Lee Cooper, Kenneth Dunton, Shu Gao, Patrick P. Hesp, Yoshiki Saito, Joe Salisbury, Maria Snoussi, Wyss W.-S. Yim*

2.1 Introduction

Earth's coastline has evolved for many thousands of years, experiencing changes to habitat, coastal dynamics and the supply of sediment from the continental interior. Relative sea level has risen in some areas, but fallen elsewhere. There is an acknowledged range in natural variability within a given region of the global coastal zone, within a context of longer-term geological processes.

Many of the regional controls on sea level involve long-term geological processes (e.g., subsidence, isostasy), and have a profound influence on controlling short-term dynamics. As sea levels fluctuate, the morphology of a coastal zone will further evolve, changing the boundary conditions of other coastal processes: circulation, waves, tides and the storage of sediment on flood plains.

Human development of coastal regions has modified pristine coastlines around the globe, by deforestation, cultivation, changes in habitat, urbanisation, agricultural impoundment and upstream changes to river flow. Humans can also influence changes in relative sea level at the local scale. For example, removal of groundwater and hydrocarbons from subterranean reservoirs may cause subsidence in nearby areas, with a concomitant rise in relative sea level. Our concern in LOICZ is not just in the magnitude of change, but also in the recent and accelerated rate of change. Our interests extend to whether alterations on the local level can cumulatively give rise to coastal zone changes of global significance.

Climate warming may also contribute significantly to sea level fluctuations. Predictions by the International Panel on Climate Change (IPCC) suggest that sea level is rising globally (15 to 95 cm by 2100) as a result of the recent warming of the ocean and the melting of ice caps (Houghton et al. 2001). As sea levels rise, coastal destabilisation may occur due to accelerated beach erosion, trapping of river sediment on flood plains and increasing water residence during floods. The predicted IPCC climate-warming scenario will undoubtedly impact some regions more than others. The Siberian coast is experiencing a reduction in offshore sea-ice cover, with a associated increase in ocean fetch, leading to higher sea levels during the open-water summer and acceleration of coastal erosion. Recent studies also suggest that tropical and temperate coastal environments are experiencing stormier conditions (i.e., increased numbers and severity of hurricanes). Will local storm surges magnify the impact of a global sea-level rise, increasing risks to humans and their infrastructure? Are there negative feedbacks to engineering options for the protection of coastal settlements?

Perhaps the largest impact on coastal stability is due to modification to the global flux of sediment to the coastal zone. Changes in global hydrology have modified the timing and intensity of floods, and therefore the effective discharge available for sediment transport. Climate shifts have varied the contributions from meltwater (snow, ice), altered the intensity of rainfall, changed drainage basin water-storage capacity, and altered precipitation and evaporation rates. Human influences have also greatly modified downstream flow. Over half of the world's rivers have seen stream-flow modification through the construction of large reservoirs. These and other rivers have also been impacted by water withdrawal for agriculture, industry and settlements.

Our understanding of the importance of submarine groundwater discharge in the coastal zone and of its processes has improved markedly in recent years; a significant impetus has been given to this understanding by the LOICZ-associated SCOR Working Group 112. The outcomes of its work are summarised in this chapter.

Human migration to the coastal zone and consequent land-use changes have also greatly impacted the stability of our coastal areas. Human impacts on the coastal zone ranges from massive (e.g., reduction in wetlands, urbanisation) to non-existent (e.g., many polar coastlines). This chapter synthesises how climate shifts and humans can affect and have affected our coasts on a global scale.

2.2 Impacts of Local, Regional and Global Sea-level Fluctuations

2.2.1 Processes and Mechanisms: Coastal Dynamics

2.2.1.1 *Impacts of Local, Regional and Global Sea-level Fluctuations*

In 1993 the LOICZ Science Plan (Holligan and de Boois 1993) commented on the problems of accurate measurement of sea-level change using tide-gauge data, and the need for more sensitive measurement techniques. The Plan also stated that "*… spatial variations in local sea level must be known in order to predict large-scale changes to coastal systems.*" (Holligan and de Boois 1993, p. 24), noting that local sea-level changes are affected by:

- tectonics,
- climatic change impacts on winds, waves and ocean circulation, and
- coastal subsidence, often exacerbated by human impacts, which can produce land/sea-level change rates higher than those of global sea-level rise.

Despite the use of more accurate global sea-level measurement techniques over the last ten years, such as satellite altimetry and geodetic levelling (see Nerem and Mitchum 2001) and the refined global viscoelastic analysis of glacio-isostatic adjustment (GIA; see Peltier 2001, 2002), there remains a need for better understanding of existing local sea-level change data and acquisition of new data.

The following is an overview of the current state of knowledge on the coastal impacts of sea-level fluctuations.

2.2.1.2 *Reconstruction of Past Changes in the Coastal Zone*

Current and predicted sea-level changes need to be considered in their geological context. The LOICZ Science Plan notes the necessity of developing historical reconstructions of sea-level change "*… in order to examine the responses of particular coastal systems to relatively large changes in external forcing that might occur in the future …*" and that "*… many of these analyses directly complement studies of the IGBP project on Past Global Changes (PAGES).*" (Holligan and de Boois 1993).

Sea-level studies from a LOICZ perspective need to be placed in the context of PAGES sea-level studies for three reasons:

1. Past sea-level changes provide a perspective on the cyclical nature of sea levels and the extent to which current and predicted sea-level changes are perturbations from natural cycles.
2. Sea-level response following the last glacial maximum of 20 000 years ago (20 ka) varied around the globe according to the coastal adjustment to the post-glacial redistribution of water and ice, and differential loading of the lithosphere.
3. Very recent geological evidence of sea levels during the last 2 000 years provides insights into subtle regional climate change linked to oceanic fluctuations.

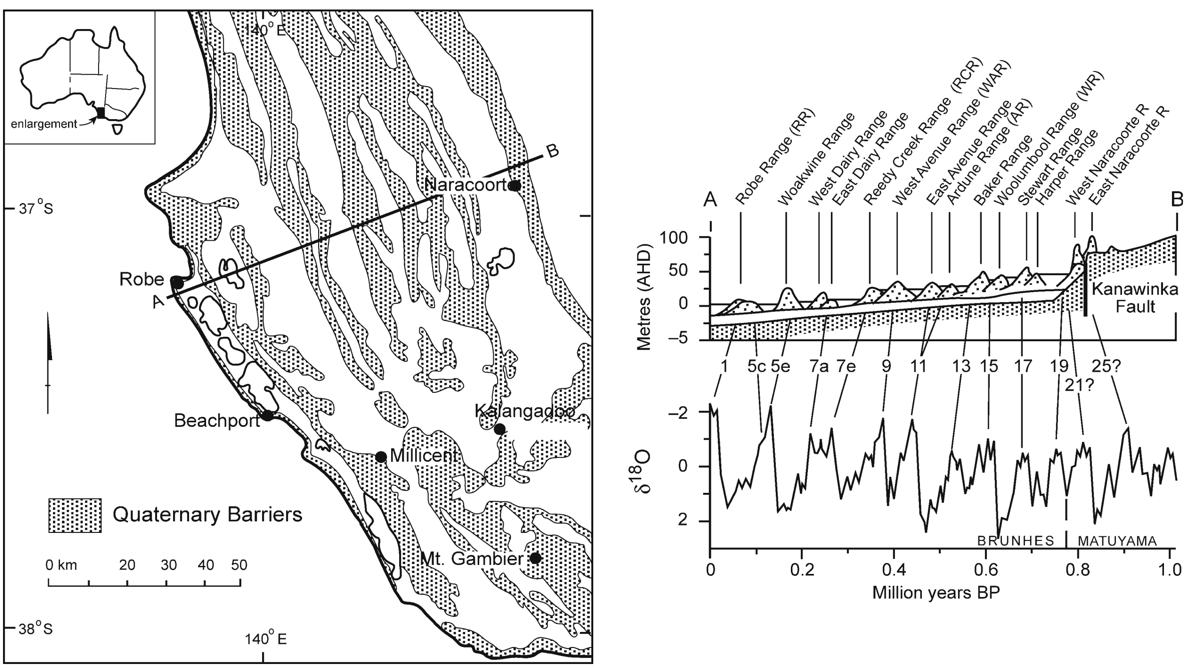


Fig. 2.1. Sea-level rise. Coastal barriers correlated with oxygen isotope changes – 800 000 years BP (from Belperio 1995)

2.2.1.2.1 *Cycles of Sea-level Change – Glacial-interglacial Cycles over 10 000 years BP*

Evidence of the cyclical nature of sea-level changes was discovered following the identification of global temperature fluctuations deduced from oxygen isotope ($^{18}O/^{16}O$) ratios of planktonic foraminifera from deep-sea sediments (Emiliani 1955). These ratios allowed interpretation of global temperature changes over time and demonstrated that a quasi-periodic cycling of climate recurred more frequently than the four major glaciations recognised from previous northern hemisphere stratigraphic studies. One good example of coastal change correlated with the oxygen isotope record across a number of glacial-interglacial cycles is from south-eastern Australia, where a series of stranded dune barriers associated with high sea-level stands has been preserved across a slowly uplifting coastal plain. The barriers, dating back to 800 000 years BP (Huntley et al. 1993, 1994), record coastal sedimentation linked to at least 10 interglacial high stands of sea level (Belperio 1995; Fig. 2.1).

Detailed climatic reconstructions for the last four major glacial cycles come from the Vostok ice-core (Petit et al. 1999), which has provided new data on the cyclical nature of global climate for glacial-interglacial cycles. These permit extrapolation of the timing and magnitude of sea-level fluctuations over the last 400 000 years, from the cyclical nature in the concentrations of CO_2 and CH_4 "greenhouse" gases, which oscillated within a well-defined range between glacial and interglacial periods. The modern elevated concentrations of CO_2 and CH_4 in the current inter-glacial high sea-level period (Raynaud et al. 2000; Fig. 2.2) are greatly elevated above the upper boundary of global gas composition for the interglacial periods as derived from the Vostok ice-core.

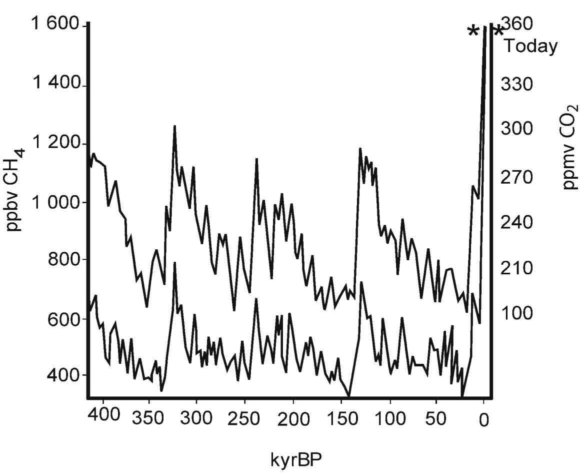


Fig. 2.2. Sea-level rise. Global greenhouse-gas concentrations from the Vostok ice-core – 400 000 years BP (from Alverson et al. 2001 adapted from Raynaud et al. 2000, after Petit et al. 1999)

This perturbation from normal cycles confirms the need for predictions of global warming and associated sea-level rise estimates as outlined by the IPCC (Houghton et al. 1996, 2001). Thus the geological evidence demonstrates a well-defined periodicity in climate-related sea-level changes. The enhanced greenhouse gas concentrations in the current interglacial indicate the potential for a sea-level response different from the previous interglacial periods. These findings have contributed to the IGBP findings that Earth systems are currently operating in a "non-analogue" state (Steffen et al. 2003).

Further geological evidence of sea-level changes across an entire glacial-interglacial cycle comes from the coral record from Barbados (Bender et al. 1979, Broecker 1979, Gallup et al. 1994, Bard et al. 1990, Blanchon and Eisenhauer 2001) and from the detailed record of coral terraces preserved on the rapidly uplifting coast of the Huon Peninsula in New Guinea. Reworking of the Huon Peninsula data has provided a close correlation with the oxygen isotope records (Chappell et al. 1996; Fig. 2.3).

2.2.1.2.2 *Postglacial Sea-level Response – the Last 20 000 Years*

Geophysical modelling of the surface of Earth has demonstrated the variable regional response of the world's coastlines to the postglacial global redistribution of ice and water (see Houghton et al. 1996). Postglacial sea-level changes are still impacting on the coast in many parts of the world, as has been shown in models of local or regional glacio-isostatic movements in the northern hemisphere and the global pattern of hydro-isostatic coastal adjustment (Houghton et al. 1996, 2001; Peltier 2001, 2002). The impact of water redistribution throughout the world's oceans has consequences for the magnitude of land/sea movements that are predicted to occur in response to the altered isostatic loads, particularly around continental margins. The results from these geophysical models are refined by geological studies.

2.2.1.2.3 *Recent Sea-level Changes – the Last 2 000 Years*

Recent studies demonstrate the potential for fine-scale resolution in reconstructing climate change during the late Holocene period. Developments with Thermal Ionisation Mass Spectrometry (TIMS) in conjunction with the measurement of Thorium/Uranium (Th/U) isotopes could provide dating resolution of 10–15 years at 2 000 years BP (Goodwin 2002). Fixed biological indicators such as coral microatolls (Smithers and Woodroffe 2000) and encrusting tubeworms (Baker and Haworth 2000) can yield high-resolution paleo sea-level datums. In particular, the microtopography of the upper surface of microatolls together with X-radiography of the annual growth banding can reflect sea-level fluctuations and even

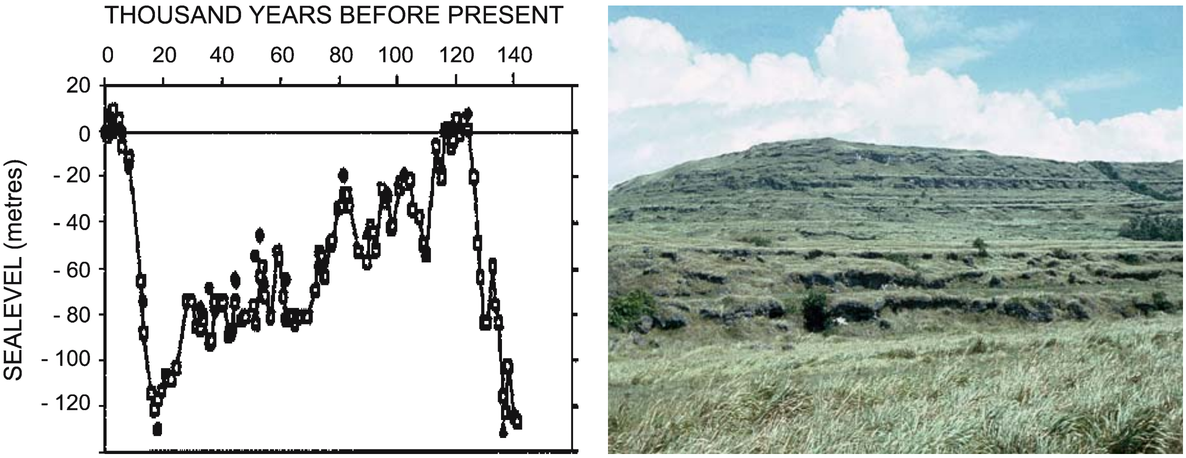


Fig. 2.3. Sea-level rise. Record of sea-level change from the Huon Peninsula, New Guinea – 125 000 yearsBP (from Chappell et al. 1996; photograph B. Pillans)

record major regional climate-induced sea-level changes, such as El Niño events in both the Pacific and Indian oceans (Woodroffe and McLean 1990, Spencer et al. 1997, Smithers and Woodroffe 2000, Woodroffe and Gagan 2000).

The paleo-climatic record is a vital tool in resolution of the debate over the global proliferation of the Mediaeval warm period (1050–690 years BP) and the Little Ice Age (575–150 years BP), especially in relation to regional variability in sea surface temperatures (SST) and ocean circulation during these periods (Goodwin 2002). Multi-decadal sea-level changes of up to 1 m, but typically ±0.5 m or less, can be detected in the recent coastal geological record (Goodwin et al. 2000, Goodwin 2002). Given that the sea-level fluctuations over the last few millennia are of a similar magnitude to those predicted for greenhouse-induced sea-level rises over the next 100 years, it is important to use the geological record to understand coastal response to sea-level changes of this magnitude. There are long-term proxy SST records for the tropical Atlantic, Pacific and Indian oceans (Dunbar and Cole 1999); Goodwin (2002) suggests that the way to link high-resolution sea-level changes with SST, and ultimately with climate models, lies in a coupled approach that derives both proxy SST and sea-level chronology in regional coral paleo-climatic studies.

2.2.1.3 *Historical Records of Sea-level Change – the Last 120 Years*

The IPCC Third Assessment Report (2001 IPPC: Houghton et al. 2001) concluded from analysis of global average sea-level rise derived from tide-gauge records that:

- the average rate of sea-level rise was less in the 19th century than in the 20th century, based on tide-gauge records spanning many decades;
- mean sea-level rise was in the range 1–2 mm yr^{-1} with a central value of 1.5 mm yr^{-1} during the 20th century; and
- there was no widespread increase in extremes apart from that associated with a change in the mean, despite a decadal variability in extremes.

Tide-gauge records measure only relative sea level, so while it is important to have long-term reliable records, it is equally important to have sites free of vertical crustal movements due to plate tectonics (to be able to correct records for glacial rebound) and to be either insensitive to small oceanographic changes or capable of accounting for these (Douglas 2001). Douglas (2001) noted the very large location bias of the northern hemisphere for long-term (> 20 years) tide-gauge sites and selected only 27 sites (with records > 70 years) from 10 regions of the globe as suitable for establishing a 20th century global rate of sea-level rise. However, sites from the relatively stable Australian continent were excluded from that analysis, thereby omitting the two longest Australian records (both > 80 years) (Houghton et al. 2001). Based on an array of long-term reliable records, Mitchell et al. (2001) calculated an average Australian sea-level rise of 0.3 mm yr^{-1}. This value is significantly lower than any of Douglas's 27 sites used for global sea-level trends. None of the values was corrected for GIA.

To obtain a clearer picture of mean sea-level trends it is important to correct the records for local and regional influences. For example, Harvey et al. (2002) identified geologic, isostatic and anthropogenic effects on long-term tide-gauge records in southern Australia and removed these signals to obtain a corrected mean sea-level trend. Elsewhere, long-term tide-gauge records have been adjusted for vertical land movements using either geological methods (Gornitz and Lebedeff 1987, Shennan and Woodworth 1992, Gornitz 1995, Peltier and Jiang 1997,

Table 2.1.
Sea-level rise. Estimates of trends from tide-gauge data (after Houghton et al. 2001)

Source	Rate (mm yr^{-1})	Vertical land movement (method)	Region
Peltier and Tushingham (1989, 1991)	2.4	ICE-3G/M1	Global
Peltier and Jiang (1997)	1.8	Geological	Global
Douglas (1997)	1.8	ICE-3G/M1	Global
Douglas (1991)	1.8	ICE-3G/M1	Global
Trupin and Wahr (1990)	1.75	ICE-3G/M1	Global
Mitrovica and Davis (1995)	1.4	PGR Model	Global
Gornitz and Lebedeff (1987)	1.2	Geological	Global
Peltier and Jiang (1997)	2.0	ICE-4G/M2	US East Coast
Peltier (1996)	1.9	ICE-4G/M2	US East Coast
Gornitz (1995)	1.5	Geological	US East Coast
Davis and Mitrovica (1996)	1.5	PGR Model	US East Coast
Lambeck et al. (1998)	1.1	PGR Model	Fenno-scandia
Shennan and Woodworth (1992)	1.0	Geological	NW Europe
Woodworth et al. (1999)	1.0	Geological	British Isles
Houghton et al. (2001)	1.07	PGR Model	East coast Australia
Houghton et al. (2001)	1.55	PGR Model	West coast Australia
Harvey et al. (2002)	0.46	Geological	South coast Australia

Woodworth et al. 1999) or post-glacial rebound models (Peltier and Tushingham 1989, 1991, Trupin and Wahr 1990, Douglas 1991, Mitrovica and Davis 1995, Peltier 1996, Peltier and Jiang 1997, Lambeck et al. 1998). The resulting estimates, reviewed by the 2001 IPCC, excluded a wide range of rates reflecting, in part, the different assumptions and methods used for estimating vertical land movement, as well as the different criteria used in selection of the tidal data (Houghton et al. 2001).

Examples of sea-level rise estimates from various regions (Table 2.1) show that:

- The North American east coast has had significantly higher rates according to Peltier (1996) than those calculated by both Gornitz (1995) and Mitrovica and Davis (1995). Houghton et al. (2001) obtained slightly higher rates using the ICE-4G/M2 model to adjust the US east coast estimates.
- European rates have been relatively lower than those of North America. This may reveal a real regional difference in sea level because of higher rates of sea-level rise for the sub-tropical gyres of the North Atlantic in recent decades (Houghton et al. 2001).
- Australian data from two long-term sites, Sydney (82-year record) and Fremantle (91-year record), included GIA corrections from the Australian-based rebound calculations of Lambeck and Nakada (1990), yielding rates of 1.07 mm yr^{-1} and 1.55 mm yr^{-1}.

Sea-level rise estimates from southern Australia, which are significantly lower than other estimates (Harvey et al. 2002), were derived from a number of tide-gauge sites with records up to 60 years and individual rates between 0.14 and 0.87 mm yr^{-1}, following correction by geological methods. The far-field data from the relatively stable Australian continent result in lower rates than the central value of 1.5 mm yr^{-1} for global average sea-level rise trend accepted by Houghton et al. (2001) in the 2001 IPCC. Douglas and Peltier (2002) also argue against the 2001 IPCC central value, suggesting that a global average should be closer to 2 mm yr^{-1}.

As noted in the LOICZ Science Plan (Holligan and de Boois 1993), there are problems of accurate measurement of sea-level change using tide-gauge data, and there is a need for more sensitive measurement techniques. Detailed analysis and careful selection of tide-gauge sites coupled with the correction of long-term tide-gauge data (particularly for GIA) has considerably improved the accuracy of sea-level trends derived from tidal data over the last ten years. The introduction of satellite altimetry following the launch of the TOPEX/POSEIDON project in 1992 provided a new tool for measuring sea surface height from space (Nerem and Mitchum 2001). Recent installation of tide gauges, such as the SEAFRAME array in the south-western Pacific (Mitchell et al. 2001), has included GPS-positioned gauges, which will soon be capable of accurate geodetic survey. With two to three decades of precision monitoring data from this type of recording instrument collected from a global array of similar sites, it should be possible to measure the acceleration in sea-level rise and to help corroborate climate models (Nerem and Mitchum 2001).

2.2.2 Evolving Morphology and Boundary Conditions

2.2.2.1 *Sea-level Changes and Impacts on Coastal Dynamics*

Geological evidence of past sea-level changes has demonstrated that localised land/sea movements are affecting the current sea-level record at different rates, over different time-scales and at different spatial scales. A major UK-based land-ocean interaction study (LOIS, Huntley et al. 2001) examined coastal response to sea-level change over the postglacial sea-level transgression. This study produced detailed simulation modelling of coastal response for a section of the east coast of the UK, based on a vast array of paleo-climate and sedimentology data over the last 7 000 years, to predict coastal erosion and accretion with the rising sea and allied changes to the tidal pattern.

In some parts of the world, geological studies have been linked to present-day measurements of sea level using tide-gauge data. Harvey et al. (2002) demonstrated geologic, isostatic and anthropogenic influences on southern Australian tide-gauge records occurring at time-scales of 10^6, 10^4 and 10^2 years, and rates of 0.07 mm yr^{-1}, 0.4 mm yr^{-1} and 2.0 mm yr^{-1}. While the impact of longer-term geological uplift rates in the south-eastern region of South Australia were clearly visible in the stranded shorelines at approximate 100 000 year intervals (Harvey et al. 2001), the impacts of these low rates of relative sea-level fall at the modern coast are harder to identify. In contrast, the human impact on subsidence rates and consequent rapid relative sea-level rise near Port Adelaide were demonstrated by landward migration of mangroves, loss of sand from metropolitan beaches and increasing problems of flooding at high tides.

Given the differential global response to the postglacial sea-level rise, some coasts have established a morphological equilibrium to a sea level that has been relatively stable or slightly higher over the last 6 000–7 000 years while other coasts are still adjusting to the postglacial sea-level rise. There are numerous studies of coastal processes including a number of texts, but the most relevant are those that examine the impact of a rising sea, such as Bird (1993) who produced an overview of submerging coasts as a sequel to his earlier work on global shoreline changes. However, before discussing coastal impacts from rising sea level, it is pertinent to examine the latest IPCC predictions for sea-level rise.

2.2.2.2 *Sea-level Rise Projections – IPCC*

The most comprehensive scientific assessment of sea-level rise projections associated with global warming comes from the IPCC in its various assessment reports. Over the last ten years, these projections have been revised downwards from the initial best-estimate in 1991 of sea-level rise as 0.65 m to the year 2100 (Houghton et al. 1991, Houghton et al. 1992). Subsequent calculations have resulted from either more qualitative expert analysis (0.61 m by 2087: Woodworth 1993), or detailed re-calculation (0.46 m by 2100; Wigley and Raper 1993). The 1996 IPCC report considered that the major conclusions reached by the 1991 Panel remained qualitatively un-

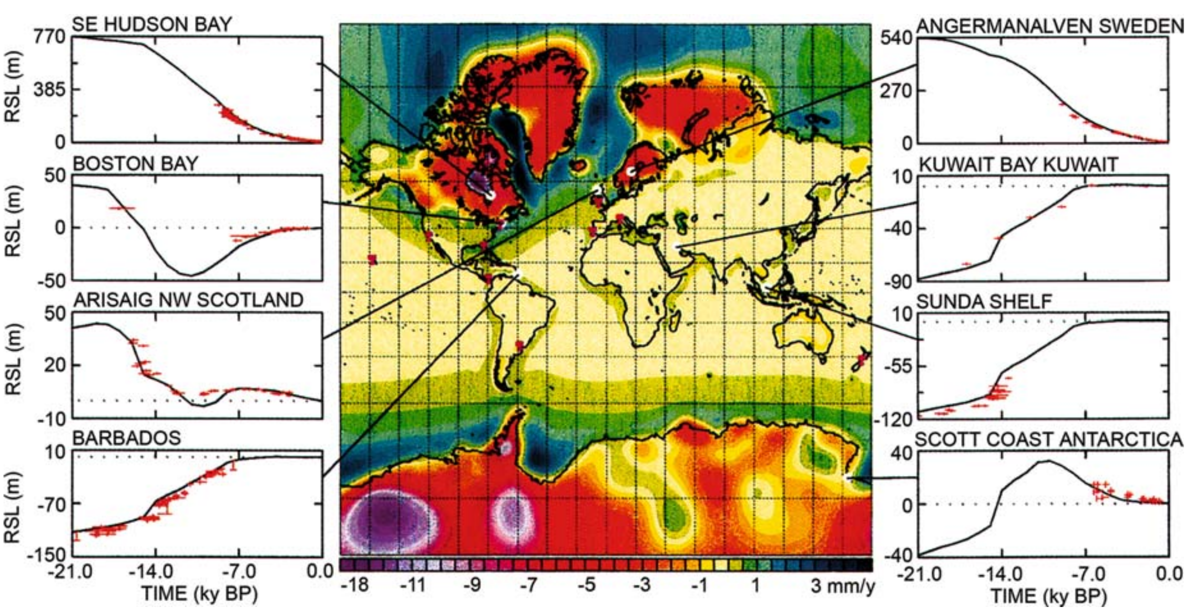


Fig. 2.4. Sea-level rise. Global isostatic response estimated from modelling (from Douglas and Peltier 2002)

changed (Houghton et al. 1996). However, all subsequent estimates of predicted sea-level rise are significantly lower than that estimated in 1991, although the 1995 evaluation warned that direct comparisons could not be made due to differences in factors such as emission scenarios and changes in radiative forcing and that the understanding of climate/sea-level relationships has not changed. The best-estimate by the 1995 Panel was that sea level would rise 49 cm by the year 2100, with a range of uncertainty of 20–86 cm. This projection is lower than that presented by the 1991 Panel due mainly to the lower temperature projections, the inclusion of a slow-down of the thermohaline circulation and changes to the glacier model (Houghton et al. 1996).

The 2001 IPCC scientific assessment (Houghton et al. 2001) reached a number of conclusions about the factors affecting current sea-level change. Over the last century, ocean thermal expansion is estimated to have contributed 0–0.7 mm yr^{-1} based on Atmosphere-Ocean General Circulation Models. The contribution from the melting of glaciers and ice-caps is estimated to range from 0.2 to 0.4 mm yr^{-1}, from observational and modelling studies which include contributions from the Greenland ice sheet (0.0–0.1 mm yr^{-1}) and from the Antarctic ice sheet (–0.2–0.0 mm yr^{-1}). Thus, the eustatic sea-level rise for the last century is estimated as between –0.8 and +2.2 mm yr^{-1}, with a central value lower than expected from the observational records (Houghton et al. 2001).

The 2001 IPCC used 35 SRES (Special Report on Emission Scenarios; Naki-envoi et al. 2000) to project a sea-level rise of 0.09–0.88 m (central value 0.48 m) for the period 1990 to 2100 (see Fig. 2.4). While this central value (not referred to as a best estimate) is similar to the best estimate of the 1995 IPCC, its range of uncertainty is larger. If present rates of terrestrial storage continue then the projections could vary by as much as –0.21 to +0.11 m, and the achievement of the central value by 2100 would require a rate of sea-level rise between 2.2 and 4.4 times the rate for the last century (Houghton et al. 2001).

2.2.2.3 *Coastal Response to a Rising Sea*

A number of coasts around the world have been subsiding in recent decades (Bird 1993, 1996, 2000), including high-latitude coasts in Siberia, Canada and Alaska. The 1995 and 2001 IPCC reports (Houghton et al. 1996, 2001) together with the relevant contributions from the IPCC Working Group II (Watson et al. 1998, McCarthy et al. 2001) outlined the key coastal areas that will be subject to the greatest impact from accelerated sea-level rise (low-lying coral islands, deltaic and coastal plains, sand beaches, barrier coasts, coastal wetlands and lagoons), and further noted the potential impact on gravel beaches and barriers, unlithified cliff coasts and ice-rich cliff coasts. A number of researchers have examined the impact of a rising sea on various types of coast (e.g., Restrepo et al. 2002, Leatherman 2001, Nicholls and Leatherman 1995, Woodroffe 1990, Ellison and Stoddart 1991, Milliman and Haq 1996), and there has been considerable research on coastal vulnerability assessment (see Sect. 2.3.3). The IPCC Working Group II in its contribution to the 2001 IPCC (McCarthy et al. 2001) identified the key potential impacts of climate change and sea-level rise on coastal systems as:

- increased coastal erosion
- inhibition of primary production processes
- more extensive coastal inundation
- higher storm-surge flooding
- landward intrusion of seawater in estuaries and aquifers
- changes in surface water quality and groundwater characteristics
- changes in the distribution of pathogenic micro-organisms
- higher sea surface temperatures
- reduced sea ice cover.

2.2.2.3.1 *Beaches, Barriers and Cliff Coasts*

About 70% of the world's sandy coasts, which occupy about 20% of the global coastline, have been retreating over the last century; 20–30% have been stable and less than 10% have been advancing (Bird 1993). Bird (1993) further argued that sea-level rise will begin to erode the stable coasts and stabilise the accreting coasts. Leatherman (2001) suggested that the figure for eroding sandy coasts is closer to 80–90% for the better-studied and better-documented US sandy coasts.

The impact of sea-level rise on sandy coasts is usually discussed in terms of the simple two-dimensional Bruun (1962) rule which asserts that sandy coasts will adjust and maintain their equilibrium in response to sea-level rise. The Bruun rule has been criticised because its assumptions rarely apply in the real world. However, Leatherman et al. (2000) computed shoreline change rates along the US east coast, producing a good correlation between sea-level rise and long-term erosion on eroding beaches. The results gave ratios of shoreline change to sea-level rise ranging from 110 to 181, compared with the ratios of 50 to 200 according to Bruun's calculations. Leatherman (2001) asserted that this confirms that the lateral beach erosion rate is always two orders of magnitude greater than the rate of sea-level rise.

While the Bruun rule may apply to locations with sufficient sediment supply, uninhibited equilibrium profile development and minimal longshore drift, these conditions are rarely all achieved in one location. Cowell and Thom (1994) attempted a model for shoreline response

Text Box 2.1. Coastal dune response to sea-level rise

Patrick P. Hesp

Sand dune systems may respond to sea-level change in a variety of ways depending on the prevailing wind and wave energy, surf zone-beach type, sediment store and supply, biogeographical province and rate of sea-level rise. The nature of the sea-level change may also be important, as a smoothly rising curve may produce significantly different results from those of a fluctuating curve that displays minor regressions or still-stands.

Sea-level rise does not necessarily equate with shoreline erosion and retreat. Foredunes have been formed and prograded to form foredune plains (including some so-called beach ridge plains) and prograded barriers in sites where sea level is rising relatively slowly and there is a significant sediment supply. Many of the US east coast and Gulf coast barriers have foredune plains that prograded from 4 000 years BP as the rate of sea-level rise slowed and sediment was delivered from the shelf and nearshore (Hesp and Short 1999). However, once the sediment supply diminished or stopped but sea level continued to rise, shoreline erosion and barrier retreat became common. Low foredunes are overwashed, high foredunes are scarped and either removed to be reformed landwards or "roll over" and gradually retreat landwards (Psuty 1992, Ritchie and Penland 1990).

Parabolic dune-fields and transgressive dune-fields may form, or have formed, as a response to rising sea or lake levels. This occurred particularly in the period 10 000 to 7 000 years BP (e.g., Pye and Bowman 1984, Thom et al. 1994, Hesp 1993, Shulmeister et al. 1993, Young et al. 1993, Pye 1983), but also at various stages throughout the mid- to late Holocene (Arbogast 2000, Loope and Arbogast 2000). The seaward edges of parabolic and transgressive dune-fields may be eroded directly by rising sea level, destabilising dunes and releasing sediment for downwind transport. This would occur particularly in regions of high alongshore and onshore sediment supply and/or in regions of high wind and wave energy (e.g., Illenberger and Rust 1988, Fryberger et al. 1990). Semi-arid and arid climates would enhance the development of transgressive dune-fields due to the lack or paucity of vegetation cover. Coastal erosion in the last 100 years has led to the initiation of a contemporary transgressive dune-field phase in some coastal sites (e.g., Froidefond and Legigan 1985, Bressolier et al. 1990).

Given that some dune-fields were initiated by sea-level transgression (Thom et al. 1981, 1992, Short 1987, 1988a, 1988b, Jelgersma et al. 1970, Klijn 1990, Hesp and Thom 1990), it is possible that changes in sea level could also be responsible for the initiation of dune phases, although there is little proof to substantiate this statement. A rise in sea level may initiate dune erosion, destabilisation and the formation of a new dune phase which largely or entirely results from the cannibalisation of older dunes. Alternatively, a few meters of sea-level regression would lead to stranding of lower beach and surf zone sands and activation of sands formerly below wave base. Such changes would be most dramatic on fine-sand, low-gradient, high-energy dissipative beaches. Christiansen and Bowman (1986) and Christiansen et al. (1990) reviewed two scenarios in which dunes may be formed by either rising (transgressive) or falling (regressive) sea levels, following Pye (1983) and after Jennings (1967). They tentatively linked a major phase of Danish dune development with falling or lower sea levels (the Little Ice Age). Sea-level regression on Lake Ontario led to the evolution of dune phases according to Davidson-Arnott and Pyskir (1988).

Since the foredune is either under immediate physical threat or can potentially become relict during sea-level rise or sea-level fall, it is often the response of the foredune that predicates to the fate of the dune-field as a whole. Some possible scenarios include:

1. *Sea-level fall:* Beach width increases from a small to a significant amount depending on beach slope (and therefore surf zone-beach type), and the amount and rate of fall. Generally, slowly falling sea level would not result in a wider beach as pioneer vegetation would colonise newly available sand.
   - a The foredune stoss slope is supplied with sediment and grows seawards and upwards. A new incipient foredune develops and eventually becomes established (Saunders and Davidson-Arnott 1990). The critical factor here is that pioneer vegetation species are able to keep up with beach width increases or progradation, and therefore the sediment is locked up in foredune development rather than being released landwards to initiate a dune-field phase. This is similar to minor to major beach progradation without any change in sea level (e.g., Hesp 1984a, 1984b). Increased storminess has little effect because the foredune is able to recover by scarp filling and revegetation.
   - b The foredune stoss slope and crest is supplied with an excess of sediment off the wider foreshore, which leads to either (*i*) local and/or more widespread death of pioneer and intermediate species, or (*ii*) sediment bypassing across the foredune. Subsequent blowout development (or supply of sediment through blowouts already present) and initiation of a phase of foredune instability and breakdown may occur.
   - c The foredune is severely scarped at the time sea/lake level starts to fall. Pioneer vegetation is absent (Saunders and Davidson-Arnott 1990) and the additional supply of sediment from the widening beach is transported over the foredune; a phase of dune instability begins. Blowout, parabolic and transgressive dune-field development is possible. A period of increased storminess would aid this process despite water-level fall.
2. *Sea-level rise:* Beach width decreases from a small to a significant amount depending on the amount of sea-level rise and surf zone beach type.
   - a The foredune stoss slope erodes, blowout development occurs, the crest increases in height and the foredune gradually retreats landwards or "rolls over" (e.g., Saunders and Davidson-Arnott 1990, Psuty 1992, Ritchie and Penland 1990, Giles and McCann 1997).
   - b The foredune may be completely destroyed, and either reformed (as a new dune) some distance landwards, or be absent for some period. Landward dunes may be re-activated or may evolve into more erosional dune types.
   - c The foredune is scarped, and is subsequently destabilised to form a foredune/blowout complex. This may gradually retreat landwards. Alternatively, parabolic, sand sheet or transgressive dune-fields of various sizes may evolve. Increased storminess merely quickens the process.
   - d Sediment supply to the system is still significant and progradation takes place despite sea-level rise. A series of foredunes is built over time to form a foredune plain (e.g., the distal ends of some barriers and spits: Hesp and Short 1999).

Some of these scenarios have been observed in the short-term (10 to 60 years), while others are merely inferred but do explain some observed dune-field patterns. Overall, a relatively wide range of medium- to long-term responses is possible for a relatively small range of initial foredune types and sea-level rise conditions. None of these scenarios for foredunes accounts for environments and coastal dune development where foredunes are absent or very poorly developed. A significant additional complication not examined here is regional wind velocities (and general climatic factors). If regional wind velocities are high, for example, foredunes may always be erosional due to regular blowout development even where sea level is rising, stable or falling, or the coast is prograding.

allowing for sea-level rise and variation in sediment availability within sandy barrier-dune complexes. Hesp and Short (1999) discussed the impact of a rising sea on dune coasts (see Text Box 2.1). There have also been attempts to model coastal responses for other types of coasts, for example, the gravel barrier and cliffed coasts of eastern Canada (Forbes et al. 1995), cliffed coasts in southern England (Bray and Hooke 1997) and cliff erosion associated with El Niño events impacting on the Californian coast (Komar 1998).

2.2.2.3.2 *Deltaic Coasts*

Deltaic coasts have a particular significance in terms of potential impact from accelerated sea-level rise because many are heavily populated and are already susceptible to inundation, subsidence, shoreline recession and sediment starvation (McCarthy et al. 2001). According to Alam (1996) subsidence rates can reach up to 20 mm yr^{-1} when compaction is combined with other tectonic effects or isostatic loading. Increased subsidence due to groundwater withdrawal alone was attributed to a 17 mm yr^{-1} rise in the relative sea level over a 35-year period for the Bangkok area of the Chao Phraya delta (Sabhasri and Suwarnarat 1996). Impacts of sediment starvation on eroding deltaic coasts have been well-documented for the Nile, Indus, Ebro and Mississippi rivers (Day et al. 1997) and the Rhone and Ebro rivers (Jiménez and Sánchez-Arcilla 1997).

River regulation and management are likely to have greater impacts than climate change for highly-regulated river deltas (Sánchez-Arcilla et al. 1998) (see Text Box 2.2). In the regulated Nile, Mackenzie and Ganges rivers land has been lost due to wave erosion on the outer deltas (McCarthy et al. 2001). Many other deltas could be affected if the rate of sediment accumulation does not match the rate of relative sea-level rise (including that due to subsidence and compaction) and the consequent increased rate of sediment removal.

2.2.2.3.3 *Coastal Wetlands*

The impact of a rising sea on coastal wetlands needs to be placed in the context of the already significant human impact on the coastal zone. For example, large areas of mangroves have been cleared globally for firewood, charcoal or to allow coastal developments such as aquaculture. Thailand alone has lost 50% of its mangroves due to clearance activities over the last 35 years (Aksornkoae 1993). Sediment flux is a key determinant of mangrove response to sea-level rise.

There are various predictions about the impact on different coasts such as low islands, high islands or protected coastal settings (McCarthy et al. 2001) dependent on factors such as sediment supply, mangrove stand composition and tidal range. However, subsiding mangrove coasts provide a good analogue for response to a rising sea, with evidence of mangrove advance inland unless locally impeded by artificial structures (see Harvey and Caton 2003). This impediment to wetland advance caused by coastal defence structures has been referred to as coastal squeeze (Nicholls and Branson 1998).

Coastal marshes respond to sea-level rise by landward horizontal colonisation in a similar manner to mangroves. They also accrete vertically and can be a good geological indicator of paleo sea levels provided caution is exercised with the interpretation, particularly in relation to sediment compaction and spatial aspects of marsh species composition (Kearney 2001). The temporal variability in marsh accretion rates is also important, with examples from Nova Scotia and the Gulf of Mexico showing localised relative sea-level rise of up to 10 mm yr^{-1} (McCarthy et al. 2001). Elsewhere, coastal marshes have difficulty keeping up with sea-level rise on subsiding coasts, as observed in southern England, north-western France and in the Venice Lagoon (Bird 1996), while rapid recession of seaward margins of marshes and mangrove swamps can occur unless there is sufficient peat accumulation or sedimentation rates. On a global scale, almost one quarter of the world's wetlands could be lost by the 2080s as a result of sea-level rise (Nicholls et al. 1999).

2.2.2.3.4 *Tropical Reef Coasts*

Over geological time, coral reef coasts have shown an ability to respond to a rising sea-level. Vertical Holocene accretion of up to 26 m has been recorded on the Great Barrier Reef, with growth rates of 6 mm yr^{-1} (Harvey 1986), and 33 m of vertical Holocene accretion have been determined for Atlantic reefs (MacIntyre et al. 1977). Consequently, it has been suggested that healthy reefs with an upper growth limit of 10 mm yr^{-1} will be able to keep up with projected rates of sea-level rise (Buddemeier and Smith 1988, Schlager 1999). However, over half of the world's coral reefs are estimated to be already at risk from human activities and many are degraded due to human impact such as pollution and increased sedimentation (Wilkinson 2000, McCarthy et al. 2001; see Text Box 2.3).

Significant climate change impact on coral reefs is likely to result from increased sea surface temperatures (SSTs) and a reduction in reef calcification. Coral bleaching resulting from loss of symbiotic algae has been predicted to become a more frequent occurrence due to increased SSTs associated with global warming (McCarthy et al. 2001, Walther et al. 2002). While some coral bleaching occurs with an annual frequency (Brown et al. 2000), large-scale periods of coral bleaching over the last 20 years have been associated with El Niño events and

Text Box 2.2. Deltaic coast dynamics

Yoshiki Saito

Deltas are one of the principal coastal landforms and an important area for human activities. Deltaic coasts are affected by changes both on the land (in the drainage basin) and in the ocean. Sea-level rise is a typical example of a change in the ocean that may severely affect the coastline. Decreases in sediment and water discharge caused by dam construction, sand dredging in river channels and water usage in drainage basins are examples of changes on the land that also impact coasts.

Fig. TB2.2.1. Coastal erosion along a muddy mangrove coast, Chao Phraya River delta. Electric poles still stand in the sea after the shoreline has retreated (photo Yoshiki Saito)

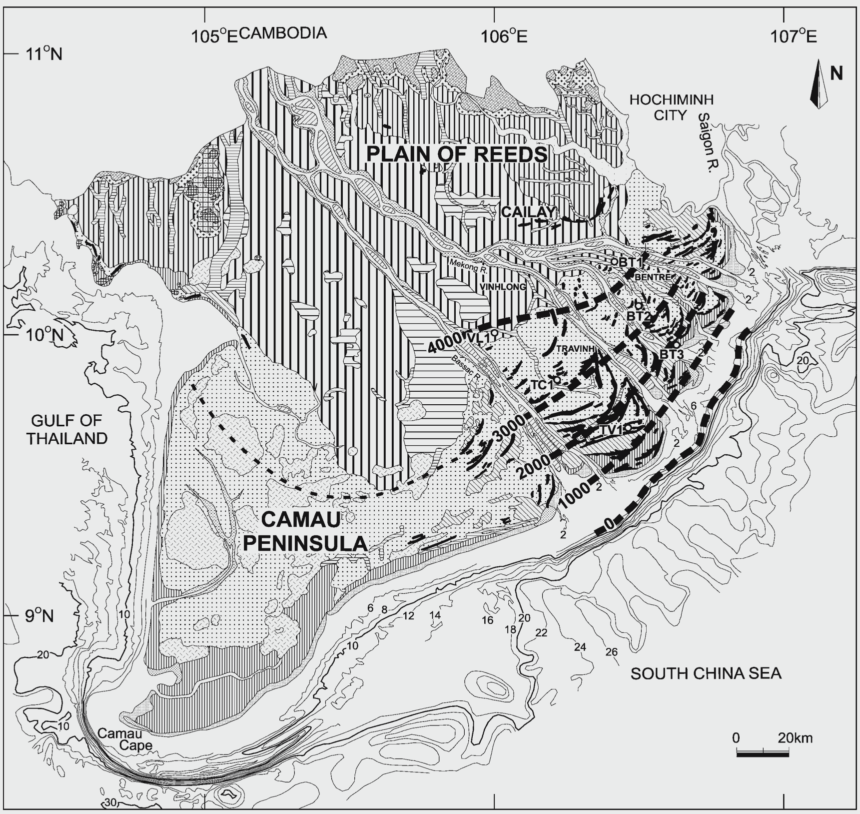


Fig. TB2.2.2. Millennial-scale paleotopography of the Mekong River delta (from Ta et al. 2002)

◀

A delta is an irregular progradation of the shoreline directly fed by a river. Therefore, seaward shoreline migration is an essential feature. Most deltas in the world today were initiated about 8 000 years ago. After the last glacial maximum, about 20 000 years BP, melting water from glaciers gave rise globally to a rapid sea-level rise except in glaciated areas, where relative sea level fell because of isostatic effects. The rising sea level resulted in the landward migration of the shoreline and the retreat of river mouths, which led globally to the formation of estuaries. The decelerated sea-level rise or slightly falling sea levels over the last 8 000 years has allowed the seaward migration of the shoreline at river mouths and the formation of deltas. Sea-level changes during the last 6 000 years varied from region to region, controlled mainly by eustatic changes (global sea-level changes), glacio-isostasy, hydro-isostasy and local tectonics, which operate even today.

At present, the formerly glaciated lands are uplifting and surrounding areas, in general, are subsiding. Typical subsiding areas are middle to southern North America, middle to southern Europe, northern Africa and the western and northern parts of the Middle East. Along these shores are found barrier islands and estuaries, which are characteristic features of coastal topography during transgression (landward shoreline migration). Exceptions are those areas where rivers with high sediment supply allow seaward shoreline migration at their mouths (e.g., Mississippi and Nile deltas). Regions far from those glaciated experienced a sea-level highstand, above the present level, about 4 000–6 000 BP, but since then relative sea level has fallen in such regions, mainly as a result of hydro-isostasy. Deltas are well-developed in these regions, in particular in Asia, middle Africa and middle to northern South America. The coasts of Australia have also experienced a stable or slightly falling sea level over the last 6 000 years, but the low sediment supply from the dry continent has allowed unfilled estuaries to persist (Saito 2001).

Wide coastal delta plains are important areas in which people live, carry on economic activities, grow or collect food. However, deltaic coasts around the world have recently become sites of serious environmental problems. One outstanding problem is erosion. A major cause of deltaic erosion is a decrease in sediment discharged from delta-forming rivers because of the construction of dams. About 30% of the global sediments previously discharged to the oceans are now trapped in reservoirs behind dams. Because of the construction of dams (including the Aswan and Aswan High dams), the Nile River mouth has experienced serious erosion, retreating more than 4 km during the last century. Over the last 30 years, dam construction and increased water consumption have caused a dramatic decrease in the amount of sediment and water discharged from the Yellow (Huanghe) River in China, which previously was the second largest river in the world after the Ganges-Brahmaputra in terms of sediment discharge. During the 1980s, sediment discharge from the Yellow River dropped to 70% of that of the 1960s–1970s and to 30% during the 1990s. Moreover, since the Xiaolangzi dam began operation in 1999, discharge has diminished to < 10% of that of the 1960s–1970s, resulting in serious coastal erosion. Another related problem is the drying up of the lower reaches of the river. In the worst years of the 1990s, the Yellow River was dry for more than 200 days over more than 500 km from the river mouth because of increased water consumption (Yang et al. 2002).

Another cause of coastal erosion is the relative sea-level rise associated with land subsidence caused by groundwater pumping. The Chao Phraya River delta of Thailand has experienced serious coastal erosion since 1970. Excess groundwater pumping in the Bangkok area has caused rapid subsidence, to more than 10 cm yr^{-1}, and the ground level has subsided more than 2 m, not only in the Bangkok metropolitan area, but also in the coastal region south of Bangkok. Relatively, sea level rose more than 50 cm during 1970–1990 in the coastal region and the shoreline has retreated up to 700 m (Saito 2001). Electric poles can be seen still standing in the sea as a result of the shoreline retreat (Fig. TB2.2.1). The increase in water depth in the near-shore zone caused by subsidence allowed increased wave energy that resulted in coastal erosion, while the cutting of mangroves along the coast accelerated the shoreline retreat. The shoreline retreat occurred even during the early stage of land subsidence, indicating that even a 10 cm subsidence (equivalent to a 10 cm relative sea-level rise) can induce serious coastal erosion. However, since 1992, the shoreline has been stable because of the regulation of groundwater pumping.

Coastal erosion occurs not only at the shoreline (intertidal zone/beaches), but also in nearshore zones. On wave-dominated coasts, waves can erode substrata to ~50 m water depth and strongly influence shoreface topography to 15 m water depth. If there is no sediment supply to the nearshore zone, coastal erosion occurs naturally. Sub-aqueous parts of deltaic coasts are occasionally eroded by waves in advance of the retreat of the shoreline, even if sediments are supplied. Even offshore of a stable shoreline, subtidal flats, the delta front platform and the upper shoreface may be gradually eroded beneath the water.

Since seaward shoreline migration occurs naturally along deltaic coasts, a stable shoreline is not a normal deltaic feature. It is important to understand the natural state of deltaic progradation. For example, the Mekong River delta has prograded steadily for the last 3 000 years at a rate of 10–20 km yr^{-1} (Ta et al. 2002, Fig. TB2.2.2). Time-series analyses, using a combination of millennial, centennial and decadal time-scales, give a clearer understanding of the nature of deltas and allow prediction or modelling future delta evolution. The evaluation of deltaic coasts and human impacts on the shoreline requires knowledge of the natural state of deltas and the natural changes that they undergo.

To prevent the erosion of present shorelines, appropriate quantities of sediments are needed above a threshold value. If the sediment supplied from rivers decreases below this value, which is different for each river and delta, deltaic coasts experience serious coastal erosion problems (Fig. TB2.2.3). The sediment discharge levels of the Nile and Yellow rivers are below this level at present.

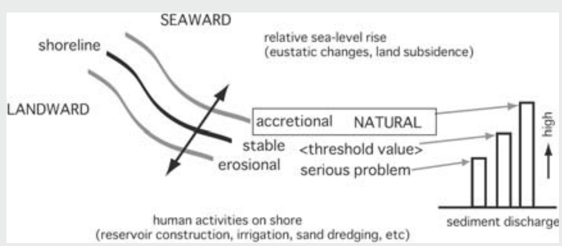


Fig. TB2.2.3. River sediment discharge and shoreline migration of deltas (from Y. Saito 2003, unpublished)

Text Box 2.3. The carbonate coasts of eastern Africa

Russell K. Arthurton

The coasts of Kenya, Tanzania and northern Mozambique have long been a locus of marine-sourced biogenic calcium carbonate sedimentation (UNEP 1998, 2001). They are part of a tectonically passive continental margin on which reefs and backreef sediments – occurring now as limestones – have formed during previous episodes of high global sea level. Their geomorphology includes terraces, cliffs and intertidal platforms, fashioned by sediment accretion, erosion and lithification in response to sea-level changes (Arthurton 2003). The limestones are important aquifers and give rise to freshwater springs in the intertidal zone.

Today's reefs date from about 6 000 BP, when global sea level had risen to near its present position from its low-stand at the last glacial maximum. They are accreting on the ocean-facing rims of limestone terraces, formerly sub-aerial but now forming intertidal to shallow subtidal patches and fringing platforms (Table TB2.3.1). Much of the biogenic carbonate debris (including broken coral) produced by wave impact on the reef front is transported landwards onto a reef bar, where the ocean swell breaks during most stages of the tide. Here the sediment becomes entrapped and enveloped by a tough, coralline algal mat, gradually raising the level of the bar, or it is carried across the bar to contribute to the sediment veneer of the backreef platform. Other biogenic contributions to the platform sediment budget are sourced on the platform itself. Besides molluscan shell debris, these include carbonate sand that has been derived as fragments from the calcified thalli of the alga *Halimeda*, which thrives in low intertidal to shallow subtidal thickets. Accumulations of these fragments form the substrata of lagoonal coral mounds and, further inshore, seagrass meadows. Landward parts of the platforms may be rock surfaces free from sediments other than beach sands or beach rocks (lithified former beach sands).

While a few island beaches protected from terrigenous sediment influx may consist exclusively of reef- and platform-derived carbonate sand, the beaches of the mainland fringing- and patch-reef coasts are formed largely of quartz sand – not carbonate, "coral" sand as is commonly supposed. The quartz sand is derived from river discharge, as well as by erosion of beach heads – usually in beach-plain sands – by extreme wave impacts and by exchanges with coastal dune systems.

During the last 6 000 years the reef bars have grown upwards to enclose lagoons, while patchy veneers of sandy carbonate debris have accumulated on the platforms (Fig. TB2.3.1). As well, beach sands have accreted over the landward parts of platforms to form beach-plains, and dune systems have developed around the mouths of sediment-charged rivers by transfer of sand from the backshore. Erosion of limestone during this period has been largely limited to the undercutting of exposed cliffs by wave impact (Fig. TB2.3.2).

Table TB2.3.1. Eastern African carbonate coast types and their components in relation to resources and susceptibility to physical change (from Kairu and Nyandwi 2000)

Primary coast type	Geomorphological components	Resources (excluding fisheries)	Susceptibility to physical change
Fringing reef coasts	Forereefs and reef aprons	Reef ecosystem, ecotourism	Dynamite fishing, bleaching, pollution and siltation affecting coral growth, storm damage
	Reef bars and backreef lagoons	Reef ecosystem, ecotourism and coastal defence	Tourism-related damage, sea-level rise
	Backreef platforms with sediment veneer	*Halimeda* thickets, seagrass meadows, seaweed culture	Sediments may be ephemeral, especially in landward parts; pollution, eutrophication
	Backreef rock platforms		Resistant to erosion
	Beach-rocks	Coastal defence	May be resistant to erosion
	Sand beaches	Tourism, recreation, coastal defence	Shoreface erosion and accretion
	Sand dunes	Coastal defence, groundwater	Beach-head erosion and accretion, aeolian deflation and accretion
	Beach plains	Agriculture, settlements, tourism	Beach-head erosion and accretion
	Rock cliffs	Coastal defence	Resistant except where soft or weathered
	Hinterland, limestone terraces	Groundwater, tourism infrastructure	Resistant except where soft or weathered
Patch reef coasts	Offshore patch reefs	Reef ecosystem, eco-tourism	Dynamite fishing, bleaching, pollution
	Intertidal flats (sediments)	Mangrove stands, seagrass meadows	Sediments may be ephemeral; erosion exacerbated by clear felling; pollution, eutrophication
	Rock platforms	Coastal defence	Resistant to erosion
	Beach-rocks	Tourism, recreation, coastal defence	May be resistant to erosion
	Sand beaches including spits	Agriculture, settlements, tourism	Shoreface erosion and accretion
	Beach plains, delta plains	Coastal defence	Beach-head erosion and accretion
	Rock cliffs	Groundwater, tourism infrastructure	Resistant except where soft or weathered
	Hinterland, limestone terraces		Resistant except where soft or weathered

◀

Over recent geological time the reef-related ecosystems have demonstrated remarkable resilience to natural forcing, notably sea-level change. But how will they cope with increasing human interventions at local to global scales over the next 50–100 years? Deterioration in the health of the primary carbonate sediment-producing biota on reefs and platforms is already reported, due not only to high sea temperatures causing coral death but also to high nutrient and contaminant levels from urbanisation, industrial development and agriculture, generated at the coast and within river catchments. Suspended sediments carried in turbid plumes from river mouths have long constrained reef development and coral growth. Reported increased suspended sediment discharge due to land-use change in catchments may be exacerbating this condition.

Will the upward accretionary growth of the reef bars keep pace with the predicted rise in global sea level, and continue to protect backreef platforms and their beaches from wave impact? Beach sand loss leading to beach-head erosion is already a problem reported from platform- and patch-reef shores. There are several possible contributing causes. Some changes may be temporary, e.g., a wave-induced, seasonal cross-shore redistribution of sand. Others may reflect longer-term, regional climate changes, or human intervention, e.g., by coastal engineering or activities in catchments changing the rate of sediment discharge. Whatever the cause of the changes, maintenance of the health of the reef ecosystem with its defensive bars will be an essential element in the protection of much of the coastline with continuing sea-level rise.

Fig. TB2.3.1. View across the intertidal platform and lagoon to the reef bar on the fringing reef coast at Diani, Kenya (photo R.S. Arthurton)

Fig. TB2.3.2. Undercut cliff bounding a backreef limestone terrace at Diani, Kenya (photo R. S. Arthurton)

Text Box 2.4. Feedbacks associated with sea-level rise along Arctic coasts

Kenneth Dunton and Lee Cooper

Arctic shelves constitute 25% of the Arctic Ocean surface area and are the largest continental shelves in the world ocean. They are heavily influenced by coastal erosion, runoff from the large rivers and sea ice, which acts as a major geological agent. Increased rates of erosion, changes in river outflow and varying ice conditions have a direct influence on the input of nutrients, organic carbon and sediments (Rouse 2000, Chapin et al. 2000, Lammers et al. 2001). Such changes have important biological and biogeochemical implications (Fig. TB2.4.1), with respect to feedbacks to the ocean-ice-atmosphere system (Moritz et al. 1990, Tynan and Demaster 1997, Aagaard et al. 1999, Morison et al. 2000, Johnson and Polyakov 2001).

Permafrost on land and in undersea deposits currently sequesters large amounts of radiatively active gases such as methane (Anisimov and Nelson 1996, Danilov 2000, Lee and Holder 2001). However, since many Arctic shorelines are erosional in nature, significant amounts of this methane and the oxidisable organic carbon stored in peat are available for release to the atmosphere. There is also a substantial dissolved organic matter component associated with the retreating shoreline, and allochthonous contributions appear to be of relatively greater importance in the Arctic than in other oceans (Wheeler et al. 1996, Wheeler et al. 1997, Guay et al. 1999, Opsahl et al. 1999). Release of greenhouse gases would have a positive feedback on the degradation of additional permafrost and release of more gas. Continuation of the current apparent decline in sea ice spatial extent and thickness (e.g., Rothrock et al. 1999) could increase water column productivity over the continental shelves, while retreat of sea ice beyond the continental shelf could lead to the disappearance of habitat for ice-associated organisms (e.g., gray whales, walruses, diving ducks and bearded seals). Shoreline erosion rates are also likely to increase with longer open-water periods without protection of sea ice from storm and wave damage. Many of these projected changes are likely to impact the communities that live near the land-sea boundary of the Arctic region.

Off-shore transport of organic matter is significant over the wide and shallow Siberian shelves (Semiletov 1999, Romankevich et al. 2000, Semiletov et al. 2001). Additional climate warming, increased precipitation and increased ultraviolet radiation fluxes could lead to higher remineralisation rates in oxidised waters and sediments on Arctic shelves (Dixon et al. 1994, Freeman et al. 2001). In the Laptev Sea, the supply of sediment and organic carbon from coastal erosion appears to exceed that from riverine input (Rachold et al. 2000), despite the outflow of the Lena River into the Laptev Sea, its mouth one of the world's largest deltas (Fig. TB2.4.2). The lengthening of the ice-free season in summer and the retreat of the summer minimum ice edge further away from the coasts during the past decade is likely to increase the transfer of wave and thermal energy to the coasts, potentially accelerating rates of coastal retreat in the future. Changes in the

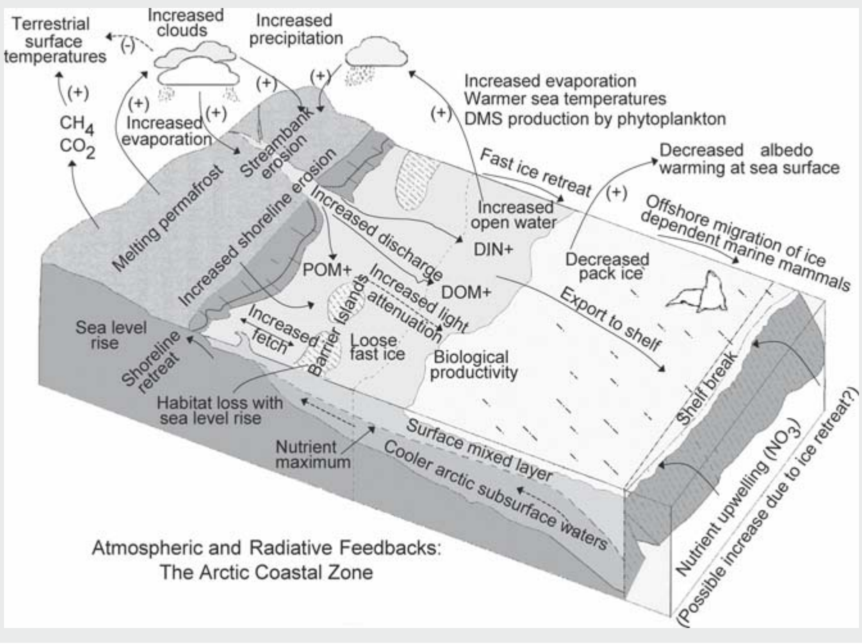


Fig. TB2.4.1. Major processes and feedbacks associated with climate change in high Arctic coastal ecosystems (from *http://arctic.bio.utk.edu/#raise*)

increased seasonal maximum temperatures (Hoegh-Guldberg 1999). In recent years, satellite-based SST anomalies have been used to predict and describe the spatial extent of mass coral bleaching events (Skirving and Guinotte 2001, see also *http://www.osdpd.noaa.gov//PSB/EPS/SST/climohot.html*), but less severe events have been more difficult to correlate with coral bleaching in other studies. Coral reefs may be differentially affected by bleaching events and in response show reduced coral and habitat diversity (McCarthy et al. 2001). In addition to bleaching in response to increasing temperatures, increased CO_2 has been predicted to reduce reef calcification rates to such an extent that its effect should be clearly manifested later in the 21st century (Kleypas et al. 1999, see Text Box 3.2 Chap. 3). A greater frequency of coral bleaching events together with a general reduction in coral reef calcification is likely to produce a geographically variable response to climate change and sea-level rise.

◀

Arctic atmosphere-ice-ocean system recorded during the past decade (Serreze et al. 2000, Huntington 2000) and the reduction in the ice season, combined with a shrinking and thinning of the Arctic sea-ice cover (Rothrock et al. 1999, Serreze et al. 2000), are likely to have profound impacts on the life cycle of marine mammals and impacts on infrastructure and development in the circum-Arctic.

Rates of coastal erosion in the Alaskan and central and eastern Siberian Arctic have been estimated as several meters to tens of meters per year (Are 1999). Paradoxically, a shortened ice season not only results in a loss of protection of the coastline but also increases the action of ice as both an erosional and transport agent. Sea ice plays a major role in the transport of eroded terrigenous sediments onto the Arctic shelf (Stierle and Eicken 2002, Reimnitz et al. 1993, Pfirman et al. 1997, Eicken 2004). The importance of ice transport processes is likely to grow with increases in wind fetch due to reduced ice cover and more frequent and stronger storm events (Proshutinsky et al. 1999). The increase in coastal erosion will be offset locally around the mouths of Arctic rivers that are expected to deliver more sediment with the warming of the hinterland (Syvitski 2002).

Arctic coastal communities depend on access to the sea and to sea ice, but are vulnerable to flooding and erosion. Key human impacts identified by arctic residents include coastal erosion, recent declines in ice extent and thickness, less stable shore-fast ice, changes in permafrost depth, gouging of shelves and coast by sea ice, pile-up of ice on shore, sea-level rise and storm hazards, including flooding. Because of the ice content of coastal sediments, rapid coastal erosion is highly variable and will not be uniform in terms of how it affects individual settlements.

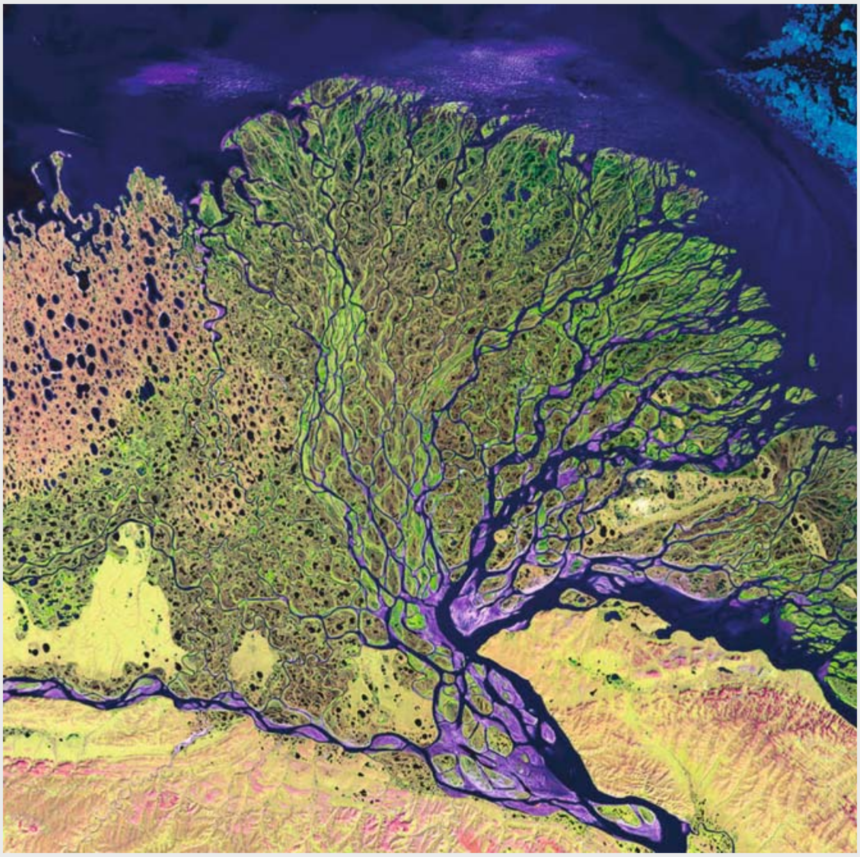


Fig. TB2.4.2.
LandSat 7 image of the Lena River delta, northeastern Siberia (from *http://www.visibleearth.nasa.gov/cgi-bin/viewrecord/18024*)

2.2.2.3.5 *High-latitude Coasts*

Climate models predict a higher than average temperature rise in high latitudes. High-latitude coasts are particularly susceptible to increased periods of ice thaw leading to a reduction of sea ice, creating greater wave exposure and exposing unlithified coastal sediments (see Text Box 2.4). There is evidence of rapid cliff recession in Siberian glacial and peri-glacial deposits in response to ice thaw (Bird 1996) and a seasonally determined active-thaw layer in high-latitude beaches and nearshore zones (Nairn et al. 1998). Any increase in global temperatures will have the effect of extending the periods of thaw and consequently increasing coastal vulnerability. Evidence of this is beginning to emerge from the rapidly eroding sandy coasts in the Gulf of St Lawrence where severe erosion in recent years has been linked to warmer winters (Forbes et al. 1997).

Another impact of global warming is the potential for the thawing of sea ice to increase areas of open water in high latitudes and create a longer fetch for wave generation. Solomon et al. (1994) demonstrated increased erosion rates from model studies on the Canadian coast using global warming predictions of the reduction of sea ice in the area. This type of impact will be exacerbated for high-latitude, low-energy mud and sand coasts such as in the Canadian Arctic Archipelago (Forbes and Taylor 1994).

2.2.3 Coastal Storms and Coastal Protection

2.2.3.1 *Increased Frequency and Intensity of Coastal Storms*

Concern has been expressed about the possible increase in the frequency and intensity of coastal storms (e.g., WASA 1998). Observed climate variability and change records show that variations in tropical and extra-tropical storm frequency and intensity are linked to inter-decadal to multi-decadal variations (Houghton et al. 2001) and that there are no significant trends over the 20th century. However, changes have been identified in both the northern hemisphere circulation, linked to the North Atlantic Oscillation, and the variability of the El Niño-Southern Oscillation (ENSO) with a move toward more frequent El Niño events since 1976. At present there is insufficient evidence to link these changes to anthropogenic forcing (Houghton et al. 2001).

There is conflicting opinion about the projected changes to storm intensity and frequency with increased warming. For example, on the issue of frequency of extra-tropical cyclones, Zhang and Wang (1997) suggested there will be fewer storms with a moister atmosphere, whereas Simmonds and Keay (2000) proposed that an increase in moisture should increase them. A number of theoretical and model-based studies predict increases of 5–10% in peak wind intensities of tropical cyclones/hurricanes and 20–30% increase of mean precipitation in some regions, although there is no evidence of projected changes in the frequency or areas of formation (Houghton et al. 2001). The climate models generally all indicate that the intensity of rainfall events will increase. Some model results presented in the 2001 IPCC report suggested that "*… precipitation extremes increase more than does the mean and the return period for extreme precipitation events decreases almost everywhere …*" (Houghton et al. 2001). There is also agreement from most models showing a mean El Niño-like response for the tropical Pacific with a shift of the mean precipitation to the east. A rise in mean sea level alone will increase flood risk.

Although there is no consensus at a global level for changes in coastal storm frequency within climate models, regional studies have predicted changes. Two model studies for north-western Europe examined the sea-level impacts of predicted changes in storm climatology and found significant increases in five-year extreme water levels (Houghton et al. 2001). Similarly, a regional study for southern Australia (Hubbert and McInnes 1999) demonstrated that increased wind speeds with cold front-associated storm surges could increase flood events in coastal localities.

The predicted sea-level rise associated with global warming must be considered in conjunction with the prospect of increased storm intensity. Raised water levels alone will allow higher energy waves to reach the coast and consequently reduce the average recurrence interval (ARI) of major storm damage events. Increased storm intensity will further reduce the ARI of storm events used for coastal planning and management purposes, such as storms with an ARI of 50 to 100 years. This collectively increases the risk to coastal populations, although locally it will depend on coastal resilience, which in turn depends on ecological, geomorphic and socio-economic variables.

The notion of the physical susceptibility to sea-level rise of natural systems was discussed by McCarthy et al. (2001), who defined the capacity of the system to respond as its resilience and resistance. While the physical concepts refer to the natural coastal system, resilience is affected by human activities. Socio-economic resilience is the capacity of a society (including its technical, institutional, economic and cultural abilities) to cope with the impacts of sea-level rise and climate change. This may involve any of the IPCC coastal response options of protection, accommodation and retreat (see Sect. 2.2.3.4). A range of technological adaptation strategies exists (Klein et al. 2000), although the use of protective works, for example, needs to be considered within the planning context of a particular country. Differences between countries in terms of physical susceptibility to sea-level rise and socio-economic resilience are highlighted by the vulnerability of small island states, which are located mainly in the tropics and subtropics. For this reason the 2001 IPCC report devoted a separate chapter to small island states in its discussion on climate change impacts, adaptation and vulnerability (McCarthy et al. 2001).

2.2.3.2 *Coastal Vulnerability Assessment*

The concept of coastal vulnerability differences between countries that have varying capacities to respond led to the notion of coastal vulnerability assessment. The drive for a global approach to coastal vulnerability assessment from the IPCC through its "Common Methodology" was intended to assess the implications and costs of human-induced climatic change on coastal systems. Vulnerability was defined as "*… a nation's ability to cope with the consequences of an acceleration in sea- level rise and other coastal impacts of global climate change.*" (IPCC 1992) and included the impact that these changes may have on socio-economic and ecological systems. The aim was to use cost-benefit analysis of vulnerable areas to assess the best response option, such as protection of the coast by defence works, accommodation of changes, retreating from vulnerable areas, or to do nothing (IPCC 1992). Results were elaborated in a number of tables to produce vulnerability classes of low, medium, high and critical, based on relative or absolute quantities. The LOICZ Implementation Plan recognised the need for detailed research in this area with a specific long-term objective for "*… improved methodologies for vulnerability assessment at the regional and global scales …*" (Pernetta and Milliman 1995).

Eastern hemisphere vulnerability studies revealed a lack of data on basic coastal topography and a lack of operational technical capacity for describing the complicated non-linear geomorphological and ecological impacts of climate change. The spatial distribution of relative sea-level rise and other coastal implications were ignored due to a lack of regional climate scenarios, as were the other potential impacts of climate change such as extreme events (McLean and Mimura 1993). It was concluded that more work was needed on broader socio-economic needs, including traditional aesthetic and cultural values such as those of subsistence economies and traditional land tenure systems. A further criticism was that the concept of vulnerability did not take into account the concept of resilience of coastal systems to the various stresses (McLean and Mimura 1993).

Text Box 2.5. Coastal Vulnerability Index (CVI)

Vivien Gornitz

Future increases in global mean sea level associated with global warming will exacerbate existing coastal hazards. The relative vulnerability of different coastal environments to sea-level rise can be compared on regional to national scales by means of a Coastal Vulnerability Index (CVI), which incorporates basic information on a number of geophysical and oceanographic factors. In its original form, the CVI was based on seven coastal "risk" variables – mean elevation, shoreline displacement, relative sea-level rise rates, mean tidal range, significant wave height, geology and geomorphology. Each risk variable was ranked on a linear scale of 1 to 5 ("very low risk" to "very high risk"), where 5 represents the highest risk (Gornitz and White 1992). A number of meteorological variables were later added and several formulae for a CVI were proposed and tested (Gornitz et al. 1994). Since they showed a high degree of correlation (Gornitz et al. 1994), the following form of the CVI was adopted:

$$\mathrm{CVI} = [(x_1 \cdot x_2 \cdot x_3 \cdot \ldots x_n)/n]^{1/2}$$

where, n = number of variables present, x = the risk classification of each variable on a scale of 1 to 5 (with 5 representing the highest risk), x_1 = mean elevation, x_2 = mean shoreline accretion/erosion rate, $x_3 \ldots x_n$ = relative sea-level change rate. The square root was introduced to compress the extreme range of scores.

The US Geological Survey (Thieler and Hammar-Klose 1999, Hammar-Klose and Thieler 2001) has adopted this basic approach with several modifications, in addition to updating and refining the original data sets. The number of variables in the CVI was reduced to six, omitting the geology variable on the grounds that it is highly correlated with geomorphology. A regional slope extending 50 km landward and seaward of the shoreline (rather than the mean elevation) was obtained from topographic and bathymetric data. Microtidal (< 2 m) coasts were assigned a high risk rating whereas macrotidal coasts (> 4 m) received a low rating, reversing the scheme originally used by Gornitz and White (1992). The US Geological Survey based their change on the influence of storms on the coast. A microtidal shoreline is always "near" high tide, and thus at greatest risk to flooding by storms.

Figure TB2.5.1 shows the CVI index applied to the United States Gulf of Mexico coast, a region at very high risk to sea-level rise, because of its generally low topography, low resistance to erosion and very high rates of relative sea-level rise, particularly in Louisiana (see Sect. 2.6.1). Very high risk areas along the US Atlantic Coast include portions of the south shore of Long Island, New York, New Jersey, the Chesapeake Bay area, Cape Hatteras, North Carolina and sections of South Carolina and Florida. On the US Pacific Coast, very high risk areas are more scattered along the southern California shore (e.g., near San Diego), near San Francisco and north of Cape Blanco, Oregon.

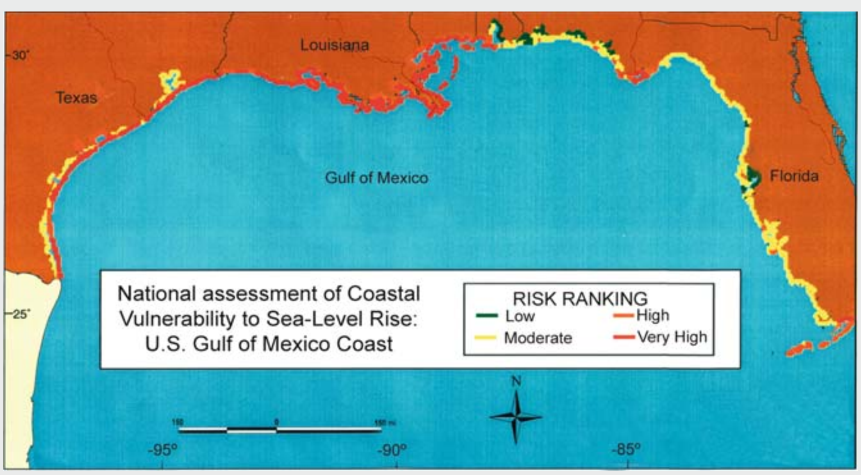


Fig. TB2.5.1. Coastal Vulnerability Index (CVI) applied to the United States Gulf of Mexico coast, a region at very high risk to sea-level rise because of its generally low topography, low resistance to erosion and very high rates of relative sea-level rise (from Thieler and Hammar-Klose 2000)

The IPCC Working Group II to the 1995 IPCC contributed studies from 23 countries that provided an estimate of land threatened by sea-level rise (Watson et al. 1996). The IPCC highlighted the vulnerability of small island states to climate change in a report on regional impacts of climate change (Watson et al. 1998) but stressed the need to consider other factors that contribute to their overall vulnerability. Subsequently, Klein and Nicholls (1999) and Harvey et al. (1999) critically analysed the "Common Methodology" approach and both evaluations proposed alternative methodologies, the latter of which has been applied in Australia. McCarthy et al. (2001) provided a review of the socio-economic impacts of vulnerability studies and studies on the economic costs of sea-level rise.

More recent attempts to use a global vulnerability approach have focused on a methodology for the synthesis and upscaling of vulnerability assessment studies (SURVAS, *http://www.survas.mdx.ac.uk*) in order to develop improved regional and global perspectives on accelerated sea-level rise and associated impacts (Nicholls and de la Vega-Leinert 2001, Nicholls 2002). The SURVAS methodology has been used in regional workshops in Europe, Africa and the Asia/Pacific region with outputs in the form of databases, workshop reports and scientific papers including a special issue of the Journal of Coastal Management (2002). Notwithstanding attempts to: (*i*) conceptualise the framework for coastal vulnerability assessment (McCarthy et al. 2001), (*ii*) modify methodologies to incorporate different socio-economic, cultural and planning contexts, or (*iii*) increase their usefulness with synthesis methodologies, it is clear that there has been a mixed success for the various global and regional approaches to coastal vulnerability assessment. One current initiative is a European Union-sponsored project DINAS COAST (*http://www.dinas-coast.net*) that is developing a simulation model and CD-based tool (DIVA) with application at local, regional and global scales, which integrates both environmental and social information to allow users to produce quantitative information on a range of coastal vulnerability indicators. Titus and Richman (2001) prepared vulnerability maps for the US Atlantic and Gulf coasts, based on elevation and not incorporating existing or projected coastal processes and climate change. The US Geological Survey has developed a critical vulnerability index for the US coastline (see Text Box 2.5).

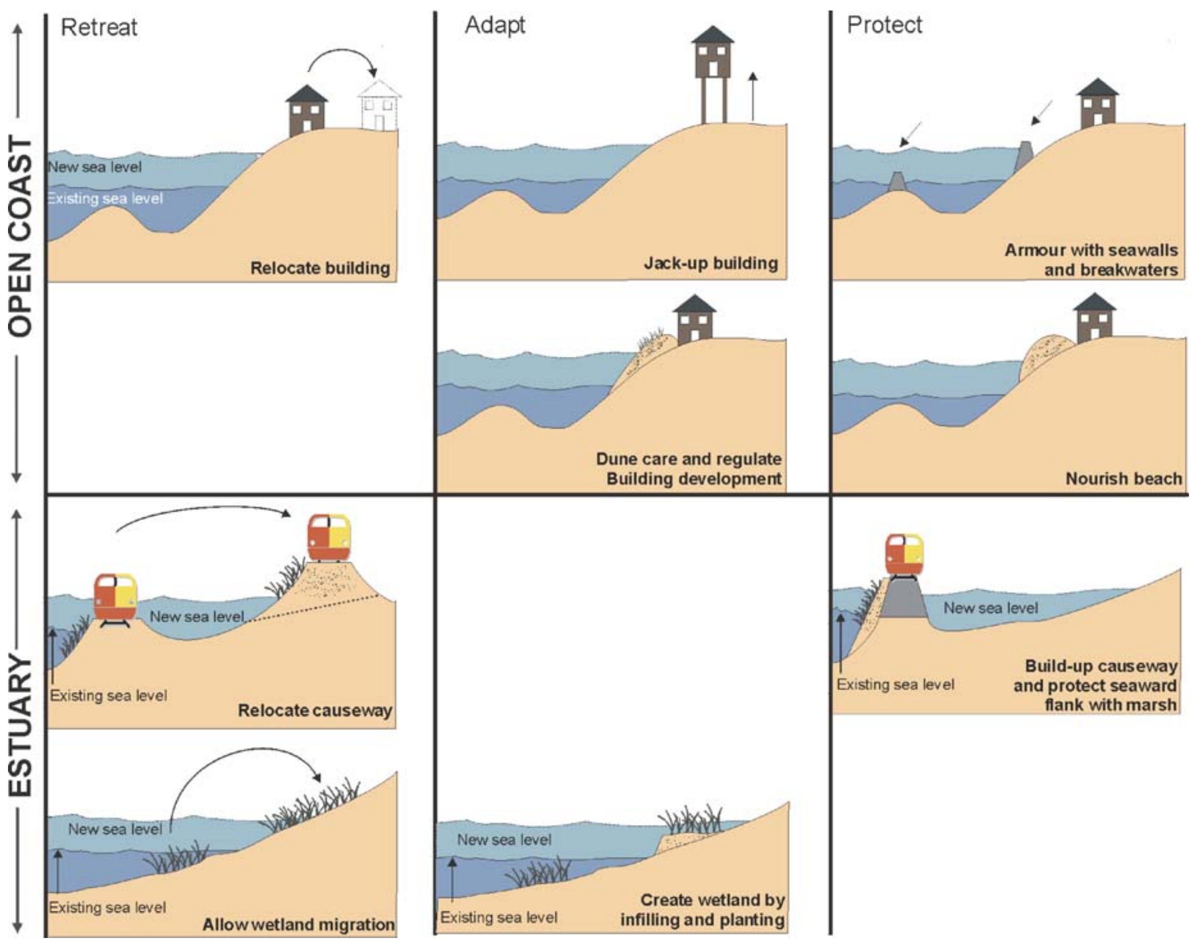


Fig. 2.5. Sea-level rise. Coastal response options for New Zealand (from Bell et al. 2001)

2.2.3.3 *Management Response to Coastal Vulnerability*

The IPCC approach to coastal adaptation (IPCC 1992) outlines three societal response options:

a *Retreat* – either a forced or a managed retreat where no attempt is made to protect the coast or property. This could involve the relocation of houses, for example, or the abandonment of various coastal land uses.
b *Accommodate* – an adjustment to the higher sea level, such as elevating coastal properties or changing land use to more compatible industries such as aquaculture.
c *Protect* – maintain the current land use with some form of engineering response involving either hard protection (e.g., seawalls) or soft protection (e.g., beach nourishment).

A summary of the various response options for open coasts and estuaries has been prepared for New Zealand coastal managers (Bell et al. 2001; Fig. 2.5). Various countries have adaptation strategies through managed retreat, including setback distances, no-build zones, rolling easements and managed realignments (McCarthy et al. 2001). South Australia has a policy based on earlier IPCC sea-level rise predictions (IPCC 1991, Harvey and Belperio 1994), i.e., that new coastal development should be capable of being reasonably protected from a 1 m sea-level rise by 2100. It recommends that site and building levels should be 0.3 m above the 100-year ARI water level and adjusted to allow for localised subsidence or uplift. Building floor levels should be an additional 0.25 m above this level, and approvals should depend on the capability to protect from a further 0.7 m of sea-level rise (e.g., by means of a bund wall or raising the building). In the case of flood-protected areas, the 100-year ARI design flood level for the development area must incorporate the extreme tide (plus surge) and storm-water events, together with wave effects. The policy also makes a general recommendation for an erosion setback distance based on 100 years of erosion (or 200 years for major development) at a site, allowing for local coastal processes, a sea-level rise of 0.3 m by 2050 and storm erosion from a series of severe storms. The evolving circumstances and management approaches for New York City, USA (see Text Box 2.6) add emphasis to the awareness about sea-level rise required in urban planning.

A distinction needs to be drawn between natural coastal vulnerability and the vulnerability of human lives and property to the effects of climate change and sea-level rise. Some coasts such as crystalline cliffed coasts may be resistant to these impacts, while coral reef or wetland coasts may respond naturally by accretion. Others such as barrier coasts may naturally migrate inland, but where humans or their property are at risk (e.g., on the US east coast) it is necessary to have societally-focused adaptation strategies (Titus 1998). In many cases, attempts to use hard protection have exacerbated the problem because of a lack of understanding of coastal processes (Doornkamp 1998, Pethick 2001) but there appears to be the beginning of a renaissance in concepts and policies for coastal management (for example, de Vries 2001).

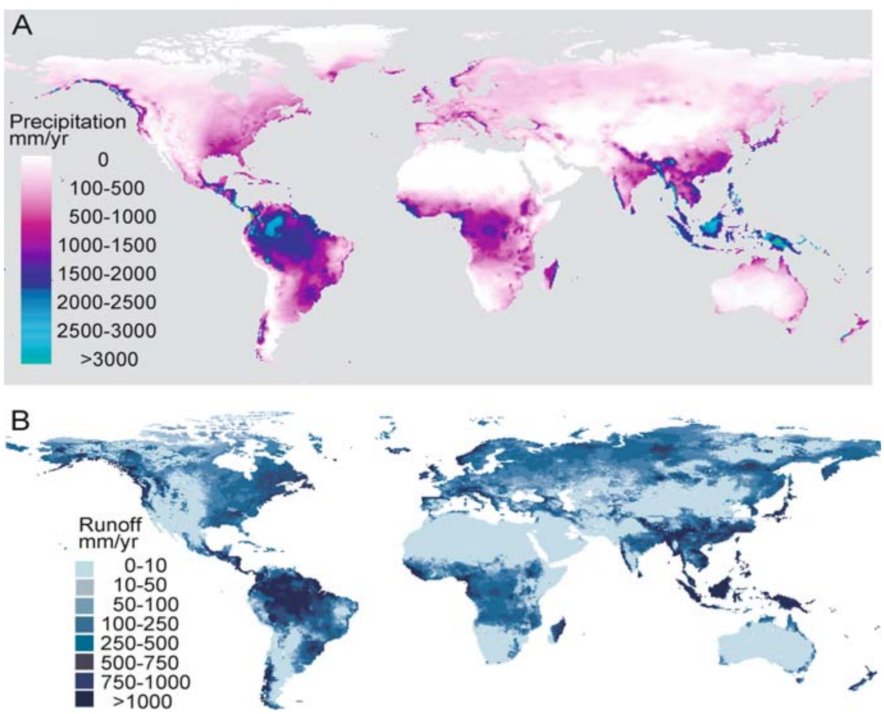


Fig. 2.6.
Water flux. **a** Global precipitation (mm yr^{-1}) (Syvitski et al. 2003). **b** Hydrological runoff (mm yr^{-1}) after accounting for all forms of evapo-transpiration and human-induced consumption. The hydrological runoff divided by the drainage area equals the water discharge (km^3 yr^{-1}) (*http://www.bafg.de/grdc.htm*)

Text Box 2.6. Coastal storms and coastal protection: New York City, USA case study

Vivien Gornitz

The New York City area will be increasingly vulnerable to storm surges, beach erosion and loss of wetlands as sea level rises. Four out of five of the New York City boroughs are located on islands that are interconnected by a large network of bridges and tunnels. Major portions of transportation arteries in the New York metropolitan area lie at elevations of three meters or less, and have been flooded by severe storms in the past. Within the past 40 years, at least three coastal storms have generated flood levels > 2 m above mean sea level, causing serious inundation and disruption to area transportation systems. Although there has been considerable interdecadal variability in storm activity during this period, no statistically significant secular trend has emerged. However, in recent years, new residential and commercial complexes have risen on landfill in lower Manhattan and have replaced decaying piers and factories at water's edge across the Hudson River in New Jersey. Ironically, the revitalisation of the New York City waterfront comes at a time when climate change may begin to threaten the shoreline.

Beaches and coastal wetlands provide the large regional urban population with recreational opportunities and also act as buffer zones against destructive storm surges. However, beaches of Long Island and New Jersey have been eroding historically, in part due to ongoing sea-level rise and in part due to construction of hard structures such as jetties and groynes. Coastal erosion of regional beaches, particularly after major storm events, is periodically reversed by expensive beach replenishment projects undertaken by the US Army Corps of Engineers. Since the 1920s, US$ 250 million has been spent on beach nourishment for just six case study sites in northern New Jersey and Long Island, New York (Gornitz et al. 2002).

Potential consequences of sea-level rise and storm hazards for the New York metropolitan area have been evaluated recently (Gornitz et al. 2002, Hartig et al. 2002). Regional sea level has climbed steadily by 22–39 cm during the 20th century. These values exceed the global mean rise of the last century (10–20 cm, Houghton et al. 2001) because of local subsidence due to ongoing glacial isostatic adjustments (Peltier 2001). Projections based on tide-gauge data and climate-model simulations with increasing levels of greenhouse gases ± sulfate aerosols suggest that regional sea level could move upward by another 24 to 108 cm by the 2080s (Fig. TB2.6.1).

Because of the increase in mean ocean levels, today even minor storms would produce coastal flooding equivalent to that produced earlier by a major storm. Floods from a 100-year storm (having a probability of recurring once in 100 years) could reach 3.1 to 3.8 m by the 2050s, and between 3.2 to 4.2 m by the 2080s. More importantly, flood return periods due to both mid-latitude and tropical cyclones (hurricanes) would shorten dramatically throughout the region. The current 100-year flood height would have an average recurrence period of 68 to 19 years by the 2050s

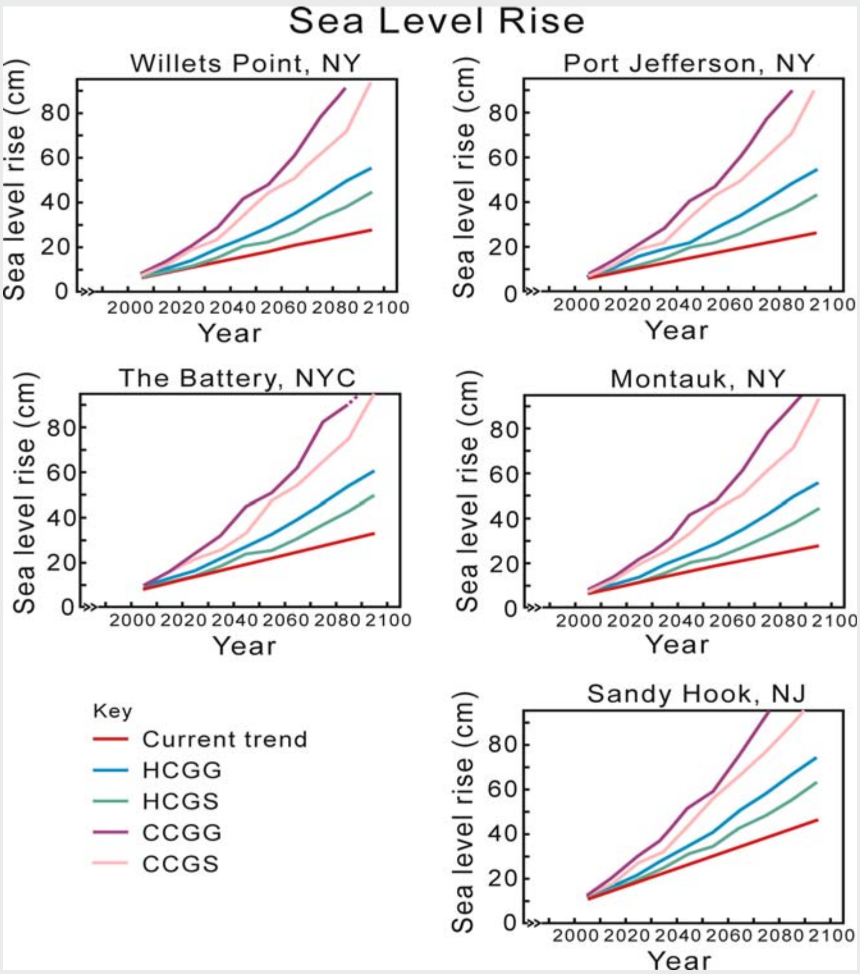


Fig. TB2.6.1.
Projections for the New York City metropolitan region based on historic tide gauge data and climate model simulations (United Kingdom Hadley Centre and Canadian Centre for Climate Modelling and Analysis) with increasing levels of greenhouse gases ± sulfate aerosols (from Gornitz et al. 2002)

◀

and 60 to 4 years by the 2080s (Fig. TB2.6.2). Beach erosion rates could increase several-fold, requiring up to 26% more sand replenishment by volume (Gornitz et al. 2002).

The salt marshes of Jamaica Bay, Gateway National Recreation Area, New York, constitute an important regional ecological resource, providing prime habitat for migratory birds and other wildlife. Initial aerial photograph analysis of several tidal salt marshes in Jamaica Bay over a 39-year period (1959–1998) showed about 12% reduction in land area. A more comprehensive remote sensing survey has revealed even more extensive marsh losses over the entire bay. Around 51% (by area) of mapped island salt marshes vanished between 1924 and 1999, with 38 percent of the losses occurring between 1974 and 1999 (Hartig et al. 2002). Although the historical rise in sea level is probably a contributing factor, no recent acceleration in this trend has been detected. Observed losses may be related to low marsh accretion rates, stemming from a sediment deficiency caused by previous dredging for navigation, armoring of the shoreline and inland development (Hartig et al. 2002). Other possible factors include erosion by storms and nutrient enrichment of the bay. Unless restoration efforts are initiated soon, the very survival of Jamaica Bay salt marshes and their wildlife populations may become increasingly precarious in the face of future sea-level rise. Buffer zones should be designated to allow for landward migration of coastal salt marshes. However, landward movement of the Jamaica Bay salt marshes could be impeded by existing seawalls and other “hard” structures, as well as by future inland development.

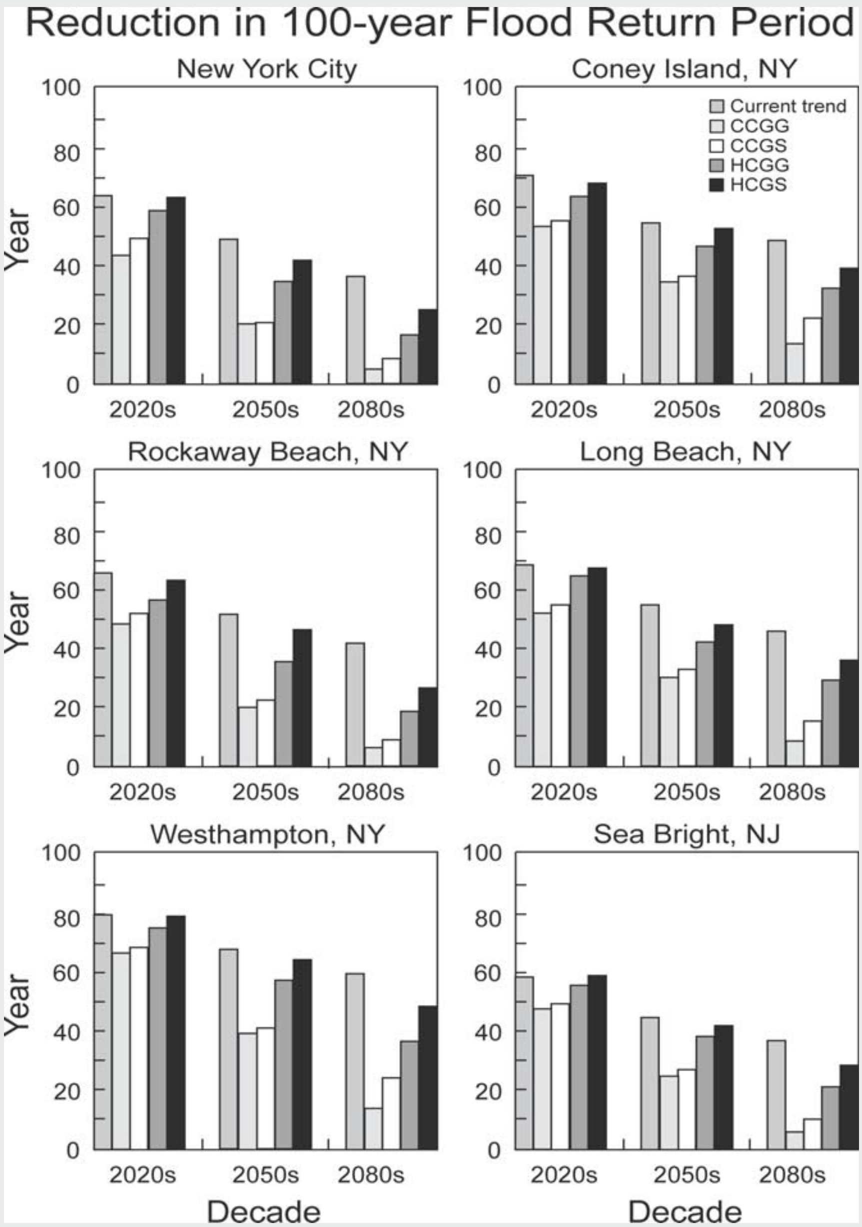


Fig. TB2.6.2. Reductions in recurrence intervals of the 100-year flood for the New York City metropolitan region due to sea-level rise based on historical data and climate model simulations (from Gornitz et al. 2002)

2.3 Changes in the Flux of Water and Sediment

2.3.1 Processes and Mechanisms

The discharge of river water to the coastline reflects the global distribution of precipitation, drainage basin area and relief, the loss of moisture back to the atmosphere through various mechanisms of evaporation and sublimation, and the time-dependent release of stored water to drainage channels (Fig. 2.6). Discharge to the coastal zone reflects this global variability.

In the sub-polar to polar regions, as well as in mountainous regions, precipitation may be initially stored in snow or ice fields and subsequently released across warmer seasons. One consequence of this initial storage is to modulate the intensity of flood waves. In less pristine regions, river flow is modulated by reservoirs and agricultural/industrial diversion schemes. Therefore, there is a wide spectrum of river mouth hydrographs (Fig. 2.7). Small maritime rivers (e.g., Annapolis) are flashy with little flow modulation. Snowmelt-dominated rivers (e.g., Fraser and Liard) show freshet flood waves that rise sharply in the spring and progressively decrease into the early summer. Glacier-dominated rivers (e.g., Homathko) discharge much of their water in the warm summer season, punctuated by outbursts and storm events. Storm-dominated rivers (e.g., Eel) reflect the duration and intensity of climatological events (e.g., El Niño storms, hurricanes). Larger rivers (e.g., Mississippi) reflect continental-scale influences such as the behaviour of the jet stream.

Rivers are the chief mechanism for the delivery of terrestrial sediment to the ocean (> 95%, Table 2.2). Sediment is delivered as bedload (sediment moved along the river bed by rolling, skipping or sliding) and suspended

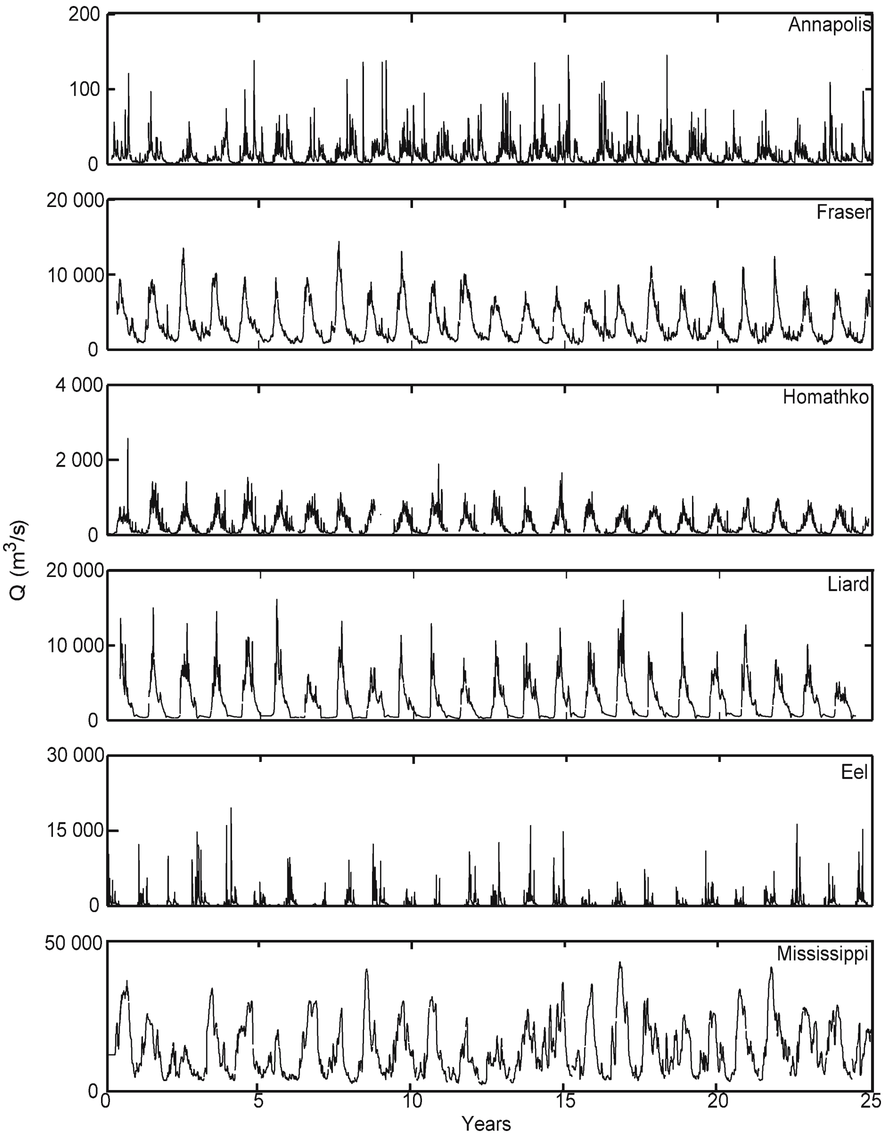


Fig. 2.7.
Water flux. Twenty-five year records of daily discharge from six North American rivers with very different hydromorphological characteristics, selected as representative of the broad spectrum (data from the U.S. Geological Survey and the Water Survey of Canada). The *Annapolis* in Nova Scotia is a small, maritime river. The *Fraser* in British Columbia is a snowmelt-dominated river and drains the Rocky Mountains. The *Homathko* is a glacier-dominated river incised into the rugged coastal mountains of British Columbia. The *Liard* in the Northwest Territories is both glacier- and snowmelt-dominated. The *Eel* is a storm-dominated river that drains the tectonically active coastal mountains of northern California. The *Mississippi* is a large highly-regulated river, strongly influenced by the jet stream

load (sediment that is fully supported by fluid flow and maintained by the upward component of fluid turbulence). Bedload is flow-dependent, difficult to measure but easier to predict; suspended load is source-dependent, relatively easy to measure but hard to predict. The proportion of suspended load to bedload increases with the size of the drainage basin, and is typically in the range of 10 : 1 to 100 : 1 of the total sediment flux to the continental margins (Meade et al. 1990).

Most rivers transport 90% of their load during 6 to 60% of their time (Fig. 2.8). At the extreme, the Eel River, which drains the steep-sloped coastal mountains of California, delivered more sediment in three days than it had carried in total over the prior 7 years. Seasonality is important when examining sediment flux patterns. Rivers fed by ice fields carry most of their sediment in mid- to late summer. Rivers dominated by snow discharge carry most sediment in early spring. Some river basins have limited and seasonal sediment sources such as snowmelt, where once the seasonal sediment is flushed out of the river, the river remains clean for the rest of the year.

A river's total sediment load depends largely on its drainage area, relief and average basin temperature: the larger the basin, the higher the mountains and the

Table 2.2. Sediment flux. Global estimates of the flux of sediment from land to the ocean (Syvitski 2003a)

Transport mechanism	Global flux (Gt yr^{-1})
Rivers:	
suspended load	18
bed load	2
dissolved load	5
Glaciers, sea ice, icebergs	2
Wind	0.7
Coastal erosion	0.4

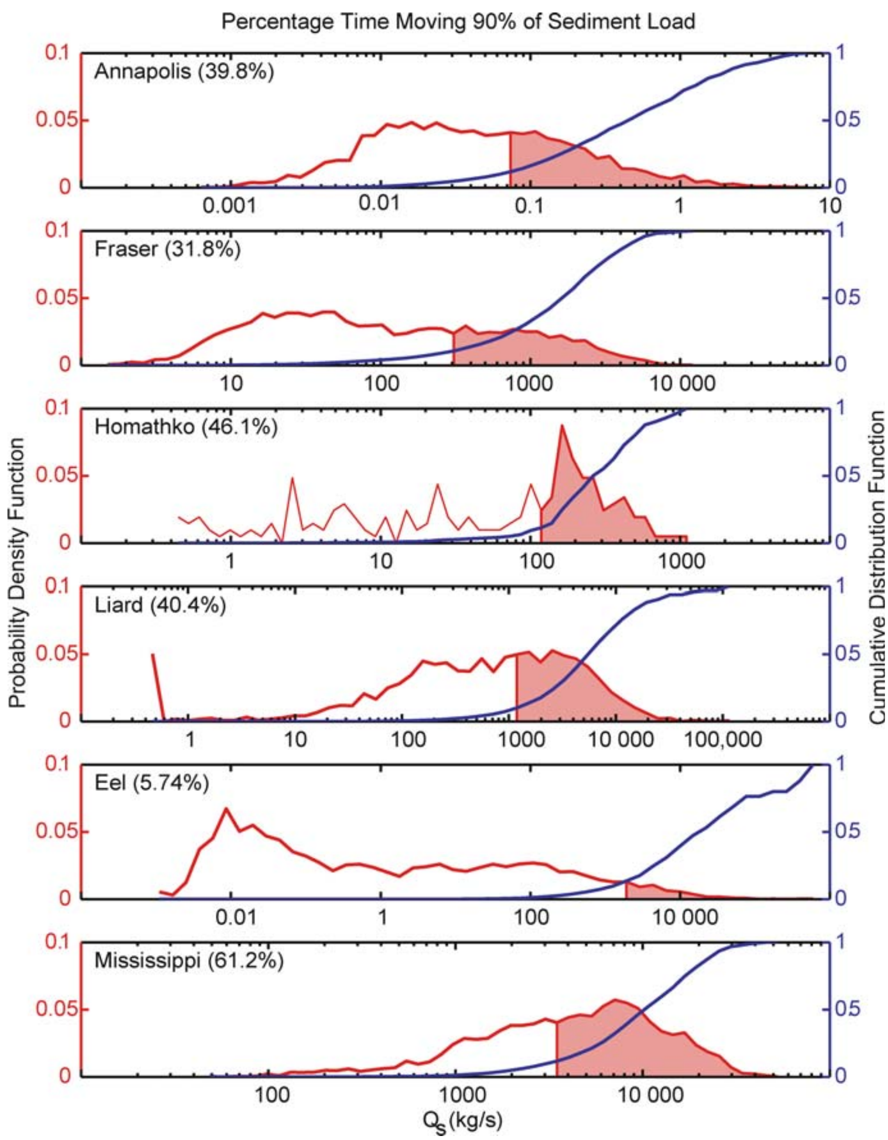


Fig. 2.8.
Sediment flux. Six selected North American rivers having different hydro-morphological characteristics (see Fig. 2.7) displaying their sediment discharge to the coast in terms of their probability frequency distribution and cumulative distribution. Displayed in red are the events that together contribute 90% of the load discharged each year. Inset boxes show the amount of time needed to carry 90% of the sediment load; for example, the Eel River will discharge 90% of its load in 5.7% of the year (21 days)

warmer the basin, the greater the load (Milliman and Syvitski 1992, Morehead et al. 2003). Regional features and geological structure also substantially influence the sediment load of rivers (Wang et al. 1998). Geological factors on sediment yield include the bedrock type being eroded (sedimentary material is more easily eroded than crystalline material), the development of extensive soils and the impact of the last ice age. For example, the runoff of the Yellow River is about 1/15 of that of the Mississippi River, 1/183 of Amazon River, and 1/2 of Nile River, but the sediment load of the Yellow River is three times the load of the Mississippi River, twice that of the Amazon River and nine times more than the Nile River. The difference in sediment concentrations is even higher. The reason is that the Yellow River flows through the Loess Plateau, and the unconsolidated loess is easily eroded. The major load of silt carried by the Yellow River is eroded mainly from its middle and lower reaches, i.e., the Loess Plateau and ancient fluvial fan (Wang et al. 1998). The effect of glaciation is seen by comparing two rivers from Alaska with similar drainage basin size and runoff: the glacial-fed Cooper River has a yield (1 200 $t\,km^{-2}\,yr^{-1}$) more than ten times larger than the non-glacial Kuskokwim River (Wang et al. 1998).

Fluvial sedimentation is most pronounced at the mouths of rivers and is dominated by the deposition of bedload at the river mouth, the main point for hydraulic transition and sedimentation under the seaward-flowing river plume. Tides and wave action rework this sediment along the coastline. Geological-scale fluctuations in sea level, glaciers, climate and earthquakes control the development of the final deposit. The net result is the development of estuaries, lagoons, fjords and deltas.

Deltas have nearly flat surface expressions of alluvial deposits formed around the mouth of a river. A marine delta survives only if sediment supply and accumulation are greater than sediment removal by waves, tidal action, submarine slides and longshore transport. Estuaries are characterised by the level of stratification within the water column: a balance of buoyancy forces set up by river discharge and processes such as those associated with tidal action which work to mix the fresh water with the denser salt-water layers.

Much of a river's sediment load will enter the sea as a surface (hypopycnal) plume: fresh water flowing into an ambient basin of saline water. A bottom (hyperpycnal) plume occurs when the sediment concentration in river water is heavy enough to create a plume density larger than the seawater density. The plume then plunges and flows along the seafloor, sometimes eroding the seafloor. Hyperpycnal plumes are often generated during exceptional flood conditions of small to medium-size rivers (Mulder and Syvitski 1995).

Rivers deliver their load as finely divided individual sediment particles and aggregated particles under the influence of hydrous oxides, organic coatings and microflora. As the river water mixes with the marine water, flocculation of silts and clays rapidly occurs. In the flocculated state, particles settle faster (by orders of magnitude) than if they were to settle individually. The influence of organic matter dominates particle dynamics in the ocean.

Seasonality in hydrological and biological events can affect the agglomeration of marine particulate matter. Zooplankton graze on river-transported flocs, producing mineral-bearing faecal pellets that rapidly settle to the seafloor. The spatial distribution and density of zooplankton is highly seasonal, often reaching maximum populations in the late spring and early fall, coincident with floods and maximum sedimentation. In temperate regions of southern Canada, the peak runoff of lowland rivers is synchronous with winter rainstorms, while the peak runoff of glacier- or snow-fed rivers is during the spring-summer period. Since the maximum biological productivity occurs during the latter period, organisms would mostly affect sedimentation of particles discharged from glacier- and snow-fed rivers (Wang et al. 1998).

2.3.2 Sediment Flux to the Coast: Climate versus Humans

Anthropogenic influences and changing climate can affect the "natural" supply and flux of sediment along hydrological pathways. Rivers and their drainage basins evolve over time, with the discharge to the ocean from modern rivers strongly influenced both by paleo-conditions within the watershed and by human perturbations (Hay 1994, Milliman and Syvitski 1992). Understanding sediment discharge across a broad time-scale allows for better predictions of the impact of humans as distinct from changes in climate. For example, the trapping of sediment by terrestrial reservoirs is fundamental to the future discharge of sediment to the coastal oceans (Hu et al. 1998).

2.3.2.1 *Paleo-fluxes before Human Influence*

Fluvial systems evolve with the landscape, so that sediment yield observed today is influenced by the geological history of the paleo-systems. Rivers like the Mississippi, for example, were fed by ice-sheet fed rivers (Ohio, Missouri) during the Pleistocene, resulting in extensive flood plain alluviation (Hay 1994). It remains difficult to determine the sediment flux from pristine rivers, given the natural variability within river systems.

While there is no accepted value for the paleo-flux of sediment to the coastal oceans, Milliman and Syvitski (1992) argued that the modern ~20 $Gt\,yr^{-1}$ global flux

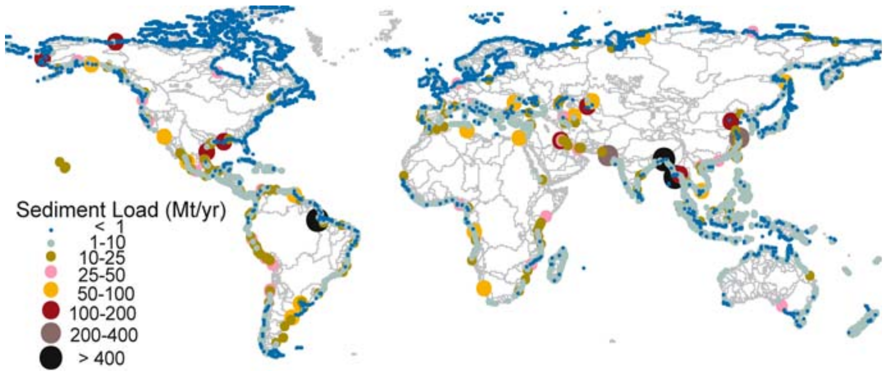


Fig. 2.9.
Sediment flux. Predictions of the sediment load of rivers with basins larger than 25 000 km^2 (Vörösmarty and Syvitski, unpubl. data 2002). Much of the world sediment is shed from the rivers that drain the Himalayas and the Tibetan Plateau

estimate (bedload plus suspended load) might have been 50% smaller about 2 000 years ago, when human impact was minimal. Changes due to humans and/or climate affect small river basins more dramatically than larger river basins, due to the modulating ability of large rivers. The predominance of studies in larger basins may therefore skew our view on paleo-flux estimates.

2.3.2.2 *Present Flux*

Milliman and Syvitski (1992) estimated the global flux of suspended sediment to the coastal zone as 18 Gt yr^{-1} using a typological approach based on 280 rivers that emphasised the importance of fluxes from small mountainous rivers. Even now and relative to their number, very few small rivers have been monitored worldwide. Small rivers are highly impacted by rare events (e.g., landslides, floods), and lack of data on these events remains a fundamental problem in determining a global flux estimate. Using digital elevation data covering the global landmass to constrain the upscaling exercise, the annual sediment flux to the global ocean is determined to be 24 Gt yr^{-1} (Syvitski 2003c) (Fig. 2.9).

Meade (1996), however, notes that any global estimates are not the sediment flux to the coastal ocean, but flux estimates to the most seaward gauging stations in the river basins. These stations are often located well inland, and more seaward filters such as deltaic and tidal flats often influence the magnitude of the sediment load reaching the coastal ocean. Examples include:

- in the Amazon River, 20% of the annually delivered load (1 Gt yr^{-1}) is retained by its delta; the remaining 80% is deposited on the continental shelf and coast.
- in the Ganges and Brahmaputra rivers, 55% of their combined annual sediment load (1.1 Gt yr^{-1}) is retained by their delta, with 36% reaching the shelf and 9% reaching the deep sea.
- in the Yellow River, 82% of the annual load (1.1 Gt yr^{-1}) is retained by its delta; the remaining 18% is deposited on the shelf and coast.

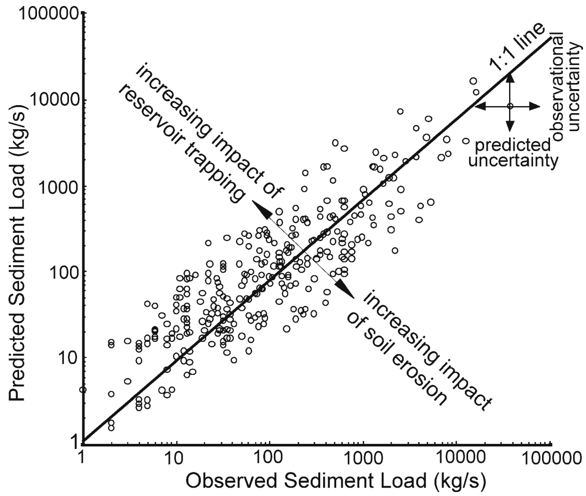


Fig. 2.10. Sediment flux. The sediment load of global rivers, based on the typological model of Syvitski et al. (2003), with

$$\overline{Q_s} = \alpha_3 A^{\alpha_4} R^{\alpha_5} e^{k\overline{T}}$$

where Q_s is long-term sediment load, A is basin area, R is river basin relief, and $\overline{T}$ is basin averaged temperature. Observational errors are globally variable and large, and relate to the short duration and quality of measurement. The scatter around the 1:1 lines is largely an indication of the impact of human activities (e.g., soil erosion or impoundment by reservoirs)

Another problem facing all coastal flux estimates is that most of the observational data covers only a few years. This leads us to question the usefulness of mean numbers for sediment discharge (Fig. 2.10). Both inter- and intra-annual variations within river basins need to be considered (Fig. 2.11); inter-annual variability can exceed an order of magnitude. Another problem with observational datasets is that they are some decades old (1960s and 1970s), with most of the global observational network now abandoned. Global estimates will need continual re-examination following construction of more dams and other engineering projects. Vörösmarty et al. (1997) estimated that approximately 30% of the global sediment flux to the coastal zone is trapped behind large reservoirs, and the coastal impact of such dam construction can be great (Hart and Long 1990).

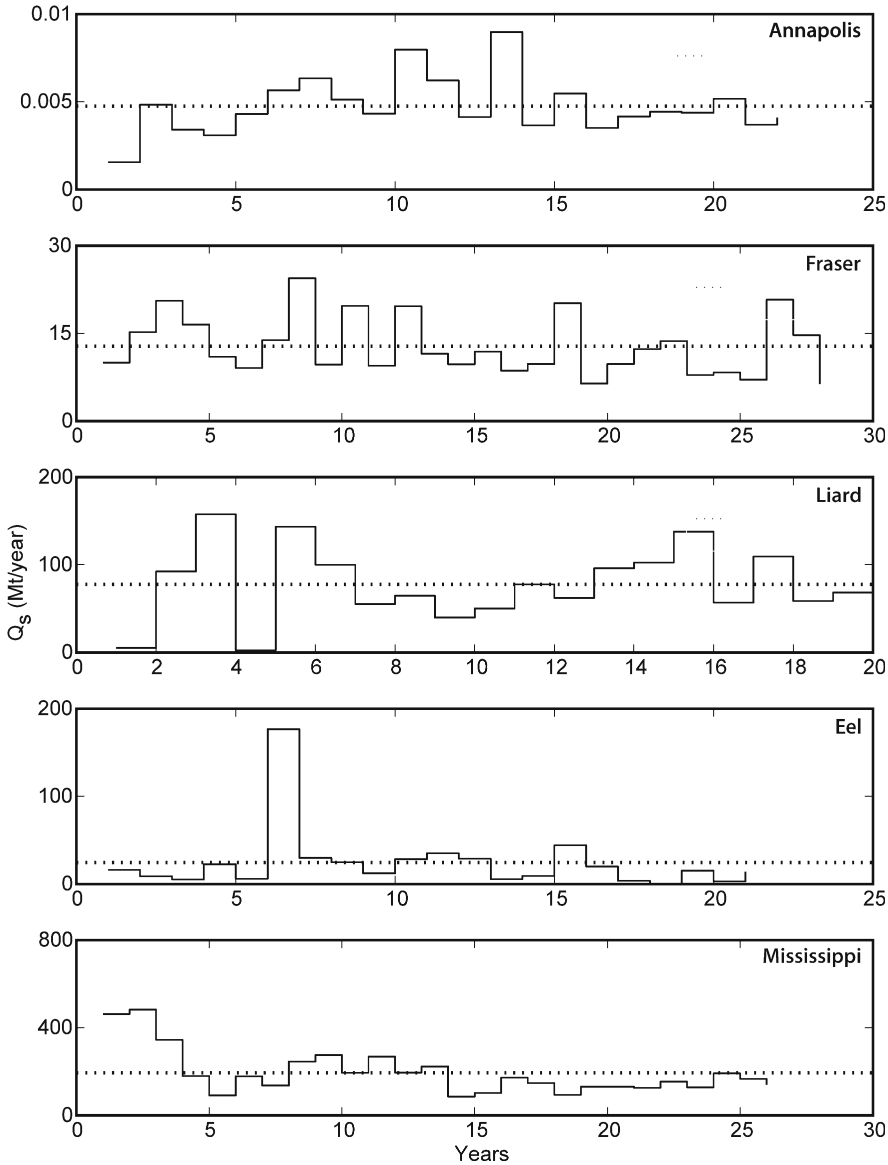


Fig. 2.11. Sediment flux. The inter-annual variability in sediment delivery to the coast of five selected rivers (see Fig. 2.7). Annual variability can range from an order of magnitude (e.g., Eel and Liard rivers) to a factor of two (e.g., Annapolis and Fraser rivers). The decreasing annual load of the Mississippi River relates to the increasing impact of sediment impoundment

Sediment is stored in large river systems across many different time-scales with little linkage between the original erosion of uplands and subsequent sediment discharge at river mouths. Ninety percent of the sediment eroded off the land surface is stored somewhere between the uplands and the sea (Meade 1996). Twentieth century erosion across the conterminous USA (5.3 Gt yr^{-1}) (Holeman 1980) was an order of magnitude higher than the fluvial discharge of sediment (0.445 Gt yr^{-1}) (Curtis et al. 1973, also see Smith et al. 2001). At the seasonal scale, sediment is stored in riverbeds and along their banks at low or falling discharges, but re-suspends at high or rising discharges. Temporarily stored sediment may be washed out of the system before peak discharge is reached. At the decade to century time-scale, sediment moves down the drainage system in a series of sediment pulses, and may take decades to gain the lowest reaches of the flood basin (Madej and Ozaki 1996). Understanding these scales will play an important role in deciphering the difference between soil erosion and sediment discharge by rivers (Meade 1996).

2.3.2.3 *Sediment Flux and Climate Change*

Recent studies point to a strong coupling of river discharge and climate oscillations. The El Niño-Southern Oscillation-induced climate changes recur on a multi-decadal timescale in general agreement with the Pacific/North American climate pattern (Inman and Jenkins 1999). A dry climate was observed in southern California from 1944 to about 1968 and a wet climate from about 1969 to the present. The dry period was characterised by consistently low sediment flux out of southern Californian rivers. The wet period has an annual suspended sediment flux about five times greater than the dry period, caused by strong El Niño events that produce floods with an average recurrence of about 5 years. The average sediment flux out of southern Californian rivers during the three major flood years was 27 times greater than the flux during the 1944–68 dry climate period. Similar trends were observed for the Eel River of northern California (Syvitski and Morehead 1999). In contrast, sediment loads are low for the Yellow River during El Niño events when the Southern Oscillation Index is negative (Hu et al. 1998), i.e., an opposite response to the impact of southern California rivers.

There is a close interdependence between climate, land use, vegetation cover density and erosion rates. After human settlement effects, climate shifts are often the major driving factor on sediment flux. For example, given a sharp rise in precipitation following a decade of relatively low rainfall in East Africa, sediment yields greatly increased (Wasson 1996). One of the largest impacts of climate change is through changes in the overall water balance with subsequent impacts on land cover density and thus erosion rates. Relatively modest shifts in average climate conditions (i.e., 1 to 2 °C, < 20% precipitation) have large impacts on the behaviour of a river's flood response and thus sediment yield (Knox 1993).

Large continents are influenced by a number of climatic phenomena over different time periods. Individual regions may respond differently to climate forcing, yielding a varied response of changes in sediment flux for a given climatic event. The response will depend on the duration of the climate fluctuation and the variability in spatial properties of such parameters as relief, geology and hydrological processes.

2.3.2.4 *Anthropogenic Influences*

Human impact on the flux of sediment to the global ocean is well recognised (Berner and Berner 1987, Milliman et al. 1987, Hu et al. 1998, Saito et al. 2001). Land use is probably the dominant control on particulate fluxes in areas of low relief and large-scale urbanisation, in contrast with mountainous regions where natural processes are likely to still dominate (Wasson 1996). Land clearing in low relief areas increases sediment yields by more than an order of magnitude (Douglas 1993), an effect that increases with decreasing drainage area.

In the wet tropics, intense rainfall coupled with deforestation, overgrazing and other poor farming practices considerably increases soil erosion (Wolanski and Spagnol 2000). In some cases the effects are catastrophic (e.g., mud slides). These practices, together with the discharge of mine tailings to rivers, have increased the sediment loads carried by rivers many times above natural backgrounds. Except where dams capture the sediment, the future for tropical estuaries and coasts is increased muddiness and increased flooding. This in turn reduces primary productivity and impacts the tourism industry with the inherent loss of aesthetics. Even in less extreme cases, increased water turbidity still leads to environmental degradation from the smothering of coral reef organisms and seagrasses (McLaughlin et al. 2003). The mud also affects the biological properties of the water and the benthic food chains in tropical river deltas, which economic planners have generally chosen to ignore. Clearly, in such systems maintenance of a healthy marine environment requires concomitant management of the land. This situation contrasts with that in developed countries in middle latitudes, where estuaries are generally suffering from sediment starvation due to extensive damming and river flow regulation (Wolanski et al. 2003a).

The Mediterranean landscape may be the most human-impacted terrain on earth. Around 75% of the average sediment yield (1 100 t $km^{-2} yr^{-1}$) of Mediterranean headwater river basins may be attributed to human activity (Dedkov and Mozzherin 1992). The terrain is naturally vulnerable to processes of erosion with its steep slopes, high relative relief, fissile sedimentary rocks, thin erodible soil covers and active tectonic settings (Woodward 1995). Severe land degradation has taken place including badland formation, representative of acute land deterioration. Rising human population exacerbates these conditions. In tropical areas of the globe, deforested land is increasing at $1 \times 10^5 km^2 yr^{-1}$ (Hu et al. 1998) and may account for the extraordinary sediment loads from Oceania discussed by Milliman and Syvitski (1992).

Where the natural sediment balance of estuaries is disturbed by an increase in a river's sediment load and/or change in the intensity of its annual flood wave, changes in bathymetry as a result of net siltation or erosion will ensue. The extent and speed of an estuarine response will depend on bathymetry, intensity of floods, tidal range and riverine sediment inflow. An estuary can change markedly in a few decades.

Impoundments provide important benefits to society through flood control, power generation, water storage and release for agriculture, industry and municipalities. Impoundments also provide a unique recreational resource (Vörösmarty et al. 1997). Negative environmental impacts include dislocation of human populations, siltation of reservoirs, downstream scouring of channels, interference with migration, life cycle and habitat of aquatic organisms, eutrophication and anoxia, increases in the occurrence and severity of stagnant-water diseases, and irretrievable water loss through reservoir evaporation and groundwater seepage. There is also the decrease in sediment supply to the ocean. Between 1951 and 1982 dams were being constructed at a rate of 900 per year. Prior to 1950 there were only eight dams in China; by 1982 the number had increased to 18 600, or 55% of the world total (with the US at 16% and Japan at 6%; Vörösmarty et al. 1997). A case study for Morocco (Text Box 2.7) highlights the effects of damming on sediment supply to the coastal zone.

The Colorado River once supplied about 150×10^6 t yr^{-1} of sediment to the Gulf of California. Sediment trapping by dams has starved the Colorado delta and this has resulted in coastal recession (Walling and Fan 2003). The Ribarroja-Mequinenza Dam on the Ebro River in Spain traps 96% of the river sediment, which has led to coastal recession at the river mouth and cessation of the sea-

Text Box 2.7. Role of reservoirs and sediments: Moroccan case study

Maria Snoussi

The suspended sediment fluxes of the main Moroccan rivers flowing into the Atlantic Ocean (Fig. TB2.7.1) were estimated to be 40×10^6 t yr^{-1}, i.e., a yield of 750 t km^{-2} yr^{-1}. This rate, which is one of the highest in Africa in terms of specific sediment yield, is probably due to the drainage basins being characterised by young mountains, extensive sedimentary rocks, irregular and often stormy precipitation and scarce vegetation. The Sebou River's exceptionally high sediment yield (995 t km^{-2} yr^{-1}) reflects the erodible rocks of its drainage area and steep slopes that cause landslides and mudflows.

In these semi-arid conditions, where rainfall occurs mostly as short and heavy storms, flood events dominate the water and sediment fluxes. For example, during the 1963 floods, the maximum water discharge of the Sebou River was 8 000 m^3 s^{-1} (about 60 times greater than the mean annual value) and that of the Moulouya River 5 200 m^3 s^{-1} (nearly 240 times greater than the mean annual discharge). Suspended matter reached several hundred g l^{-1} during the flood events. While land erosion and sediment delivery in this semi-arid region are products of physical factors (e.g., climate, topography, soil erodability and the local vegetation status), human activities (deforestation, overgrazing and damming) are exacerbating these processes.

Damming has increased over recent decades to better manage the water shortages in Morocco caused by recurrent droughts. However, the reservoirs have experienced siltation from the high rates of natural and accelerated erosion in the hinterland. The annual sedimentation rate in the main reservoirs averages 50×10^6 m^3 yr^{-1}. This high siltation rate has serious environmental and socio-economic impacts, because it reduces the reservoir capacity and may be affecting the morphological equilibrium of the coastline.

The Sebou River basin is a clear example of the effects of the construction of reservoirs on river sediment fluxes. In the period 1940–1972, before dam construction, the average suspended sediment input to the Atlantic Ocean was about 34×10^6 t yr^{-1}. Since construction of the reservoirs, > 95% of the total sediment load has been trapped (Haida 2000). The calculated trap efficiency is 85–99%, and the lifespan of the reservoirs has diminished from 540 years to as little as 42 years. Similarly, the Moulouya River now delivers to the Mediterranean Sea only 7% of the sediment load transported before it was dammed (Snoussi et al. 2002); the Mohamed V reservoir will fill with sediment within 59 years, having lost 35% of its storage capacity between 1967 and 1991. It is estimated that by 2030, 70 000 ha of irrigated land and 300 MW of electricity will be lost as a consequence of the high rates of dam siltation.

Considering all the dams, sediment trapping has reduced the catchment areas as effective sources of coastal sediment by 60–70%, which may have a profound effect on the morphological evolution of the coastline. However, it is difficult to isolate the effects of damming on the shoreline evolution, since influences other than fluvial discharge (e.g., human activities at the coast) affect the coast at different rates and times.

The potential effects of the construction of the Mohamed V dam on the Moulouya shoreline morphology were examined by comparison of two sets of aerial photographs (1958 and 1988). Before construction of the dam (1958), the lower Moulouya River was sinuous to meandering and the mouth was much wider than it is now. Fluvial sediment discharge was sufficient to support progradation of deltaic deposits in the eastern part of the river mouth. Since construction of the Mohamed V dam, the river mouth and coastline have changed markedly. The influence of marine waves has increased because of weaker fluvial hydraulic power, leading to reworking of shoreline sediments, narrowing of the river mouth and accumulation of mouth bars. Net littoral transport is about 165 000 m^3 yr^{-1}. Wave-induced sand transport is directed westwards and has led to the accretion of the west coast, while the east coast, no longer fed by fluvial inputs, has retreated. Many other inlets, apart from those that are stabilised (Loukkos, Sebou and BouRegreg) have spits directed westward along the coastline. In some cases marine storms transport enough sand to fill the inlets periodically (Moulay Bouselham) or completely (Oued Massa). These changes in coastal geomorphology are probably largely due to the reduction of flow discharges by damming. In the Sebou River, fluvial competence has become very weak and now the estuary is not flushed as frequently.

In summary, the semi-arid fluvial fluxes to the coast depend strongly on climatic variations. At the seasonal scale, fluvial input occurs only during flood events (a few days per year); in non-dammed rivers, a large amount of suspended sediment reaches the coast. At other times, the rivers have weak flow or become dry, reinforcing the marine influence at the inlets. The construction of dams during recent decades has exacerbated sediment and water impoundment, while the land-ocean interface has become dominated by marine forcing. The projections of climate change trends over the next 20 years, according to IPCC methodology, predict for Morocco a general decrease of about 4% annual precipitation, a 15% decrease of surface water discharge and an increase in the frequency of extreme events (floods and droughts). In such conditions, the construction of more dams is likely to have serious environmental and related societal impacts on the coastal zone.

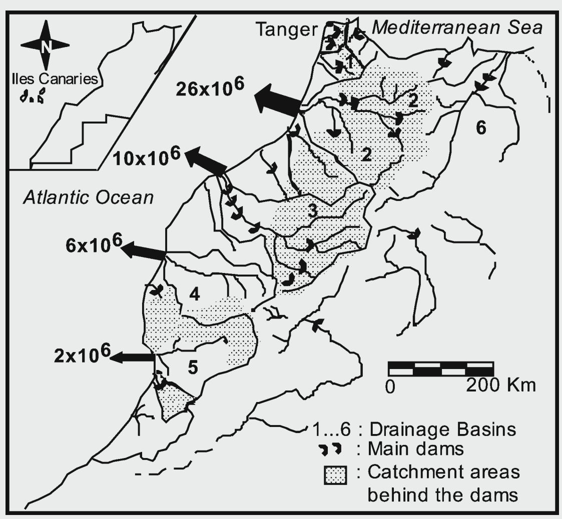


Fig. TB2.7.1. Suspended sediment discharges (t yr^{-1}) of the main Moroccan rivers into the Atlantic Ocean before the construction of dams. The *shaded areas* represent catchments for which sediment has been impounded following the construction of dams ward progradation of the delta (Guillen and Palanques 1997; Jimenez and Sanchez-Arcilla 1993). The 40% decrease in suspended sediment load between 1963 and 1989 in the Mississippi River may be the major cause for the recession of the Mississippi deltaic coast (Walling and Fan 2003).

Water diversion can also decrease sediment flow and generate coastal erosion. For instance, water diversion from China's Luanhe River has decreased the riverine sediment load by 95% and has resulted in the delta's recession at a rate of 17.4 m yr^{-1} (Qian 1994).

This story is repeated in the Nile River, which carried about 135×10^6 t yr^{-1} of sediment before construction of the Aswan High Dam (Stanley and Warne 1993). For millennia, annual floods provided Egypt with much-needed water to irrigate farmers' fields. The historic annual sediment input to the Nile River delta also helped offset geologic subsidence rates that range from < 1 mm yr^{-1} to > 4 mm yr^{-1} in the north-eastern delta region (Stanley and Warne 1993). Before completion of the High Aswan Dam in 1964, the Nile River delivered an annual average of ~84 km^3 of water and ~124×10^6 tonnes of sediment to the coast, plus an additional 9.5×10^6 tonnes of suspended sediments deposited on the Nile floodplains. Subsequently, water reaching the coast has been reduced by 80% and sediment loads by over 98% (Stanley and Warne 1993, El-Sayed 1996). The only fresh sediment now reaching the coast comes via longshore transport and aeolian activity. As a consequence, erosion along parts of the shoreline has intensified and salinisation of cultivated land has increased. With 98% of this sediment now trapped in the reservoirs, coastal erosion is intense – the Rosetta and Arietta promontories are eroding at the rates of 106 m yr^{-1} and 10 m yr^{-1}.

In semi-arid regions, river floods can be suppressed as a result of large dams. The balance between the scouring of the estuary during occasional river floods and the regular import of coastal zone sediment into the estuary by tidal pumping is then disturbed. The estuary may subsequently silt up, as occurred with the Ord River estuary in north-western tropical Australia (Wolanski et al. 2001). Macro-tides drive rapid tidal pumping and the estuarine bathymetry can change rapidly. Hence, the Ord River estuary has silted measurably by 30×10^6 m^3 over the last 30 years, and the estuarine cross-sectional area has decreased by about 50%. The Ord River estuary may have been made geomorphologically unstable by dams suppressing large river floods. Such effects are likely to be more prevalent for large dams in arid areas because they are designed to store water for several years and consequently capture most of the water from rare, large flood events; in humid areas dams are filled annually or seasonally.

When sediment from human-induced soil erosion exceeds the trapping capacity of the estuary, mud deposits in coastal waters. This process is exacerbated by reclamation of estuarine wetlands reclaimed for farming and for settlement developments (Wolanski et al. 2004). Here, the change in coastal properties may be very rapid, occurring within a few decades. Examples of this are found in bays along the Queensland coast adjacent to the Great Barrier Reef, which have become permanently muddy in only a few decades following land clearing and accelerated soil erosion (Wolanski and Duke 2002).

Reduced sediment loads to rivers through damming increases coastal erosion and deterioration of coastal marine ecosystems. Following completion of the Aswan Dam in 1964, the sardine fish catch in waters adjacent to the Nile River delta was reduced by 95% in response to reduced nutrient discharge and the delta shrank rapidly (Hu et al. 1998). Recently, with the increased use of artificial fertilisers and the expanded croplands in its delta region, nutrient loads to the Nile have increased and some fisheries stocks have improved or been replenished (Nixon 2003). After the US catchment of the Colorado River was dammed, sediment and nutrient discharge plummeted and the shrimp catch in Baja California collapsed (Hu et al. 1998). Completion of the Kotri Barrage on the Indus River in 1956 resulted in fish catches decreasing by a factor of three (Hu et al. 1998). Similar conditions occurred in the Bohai Sea when the sediment discharge of the Yellow River was reduced along with water and nutrient discharge; the shrimp fishery has decreased by 85% and the percentage of high-quality fish catch has declined by an order of magnitude (Hu et al. 1998). About 2 500 years ago the Yellow River was not muddy and its sediment discharge was one-tenth that of 30 years ago (Milliman et al. 1987, Saito et al. 2001) when it peaked in response to rapid cultivation of the Loess Plateau. A combination of soil preservation practices in the 1980s and dam construction (3 380 reservoirs and another 30 000 diversion works of various scales) have reduced both water and sediment discharge. The Yellow River now runs dry for many months of the year; in contrast, the river flooded on average every three years over the preceding 4 000 years (Saito et al. 1994).

2.3.2.5 *Near-future Sediment Flux*

The future flux of sediment to the coastal oceans will continue to be influenced by humans and/or climate change. Determining the balance between increasing sediment loads (due to land use, engineering, climate change and climate variability) and decreasing sediment loads (due to reservoirs, engineering, climate change and climate variability) is of utmost importance for sound coastal zone and resource management. In general, the future load of rivers should be less than the present estimates, mostly because of the construction of large dams. This projection may be in error, as we do not fully comprehend the balance between sediment retention

Text Box 2.8. Satellite monitoring of water turbidity in a coastal system: northern Gulf of Mexico[1]

Joe Salisbury and Janet W. Campbell

Fluvial input and processes of wind-driven re-suspension and transport control the distribution of suspended sediment in river-dominated coastal regions. The influences of discharge and winds on surface sediment concentration can be explored by analysing the covariance between these variables. Recently these relationships were investigated in the northern Gulf of Mexico using satellite-derived wind and sediment concentration data (Salisbury et al. 2001). Temporal correlation coefficients were mapped at pixel level for time-series of wind stress and sediment concentration, and Mississippi River discharge and sediment concentrations.

Figure TB2.8.1 shows the time-series at two locations to illustrate the degree of coherence between signals where there is a high positive correlation between discharge and sediment concentration ($r > 0.7$, see Fig. TB2.8.2a), and between wind stress and sediment ($r > 0.6$, see Fig. TB2.8.3b). Correlation maps based on the time series of 8-day averages for the period 20 September 1997 to 31 December 2000 reveal the long-term patterns (Figs. TB2.8.2 and TB2.8.3). A region of high correlation ($r > 0.7$) between the Mississippi River discharge and sediment concentrations (Fig. TB 2.8.2) was located near the delta and a region of significant but lower correlations extended eastward toward the Alabama coast. This region of fluvial influence was spatially separate from the regions where wind stress and sediment correlations were significant (Fig. TB2.8.3). The wind-influenced regions are associated with shallow shelf areas, as one might expect. The boundary of the wind-influenced region off the Louisiana–Texas coast is aligned with the 100 m isobath and the waters with highest correlation ($r > 0.6$) had depths < 50 m.

Maps of the correlation between suspended sediment concentration and river discharge indicate regions that are fluvially influenced, whereas maps of the correlation between wind stress and sediment indicate regions where wind-mixing accounts for sediment re-suspension and subsequent transport. The regions of positive wind and sediment correlation are spatially disjointed from regions of positive discharge and sediment correlation. This indicates dominance by one of the two sediment mobilisation and/or transport processes (i.e., sediment delivery by rivers, wind-driven re-suspension and subsequent transport). It is probable that influences of winds and discharge on sediment distributions can be investigated independently. Using these methods, investigators interested in ecosystems dominated by one process or the other can confine the focus of their work. Further, spatio-temporal correlation methods represent an opportunity to study the transformation and fate of river- and wind-influenced constituents.

[1] Figures TB2.8.1–TB2.8.3 are reprinted from Deep Sea Research II, vol 51, No. 10–11, pp 1187–1203, Salisbury et al.: "On the seasonal correlation of surface particle fields with wind stress and Mississippi discharge in the northern Gulf of Mexico." Copyright 2004, with permission from Elsevier.

schemes and soil erosion perturbations. Time-series data are needed to determine trends, with a focus on the last 20 years. These data are often lacking and new methods need to be developed (or old ones reassessed) to effectively utilise available data for water discharge. Globally, we need to determine:

a How long until we fill the terrestrial sediment sinks (natural and artificial)?
b What effect will the resulting reservoir state have on the coastal zone and the global sediment flux?
c What are the sensitivities of local and regional coastal settings to erosion on a global scale?

When modelling the possible future sediment flux, economics needs to be considered. The effect of human development and land use is vital in understanding the global sediment flux and regional variations. The global volume of sediment entering the coastal zone may not be the important variable; the change in sediment yield on a regional basis may be of much more importance. For example, sediment-starved regions may undergo erosion, while sediment-inundated regions may experience biological and ecosystem consequences such as burial of benthic biota.

Historical land-use and sediment discharge response has come a full circle for the eastern seaboard of the USA (Pasternack et al. 2001). After European settlement (post-1740) sedimentation rates increased eight-fold through early deforestation and agriculture (1750–1820), then increased another three-fold during the period of peak deforestation and intensive agriculture (1820–1920), and finally were reduced by an order of magnitude (i.e., close to pre-colonisation values) during the period of dam-building and urbanisation (1920 to present). A similar set of histories for other regions must be completed before we can understand and predict the global flux of sediment.

The combination of climate (drying) and human water utilisation drive many hydrological and erosional systems. Two situations might be considered:

1. regions that become moister and start generating runoff, thereby initiating sediment transport to the ocean, and, more probably,
2. regions that cease water flowing to the ocean because of a combination of drying and water utilisation by growing populations.

Important regions of runoff change include the Mediterranean basin, sub-Saharan Africa, southwestern North America, central Asia and eastern South America. These regions similarly witness the impact of humans on scarce water resources. Research must identify the population thresholds and behaviours that have strong hydrological and erosional effects. Some coastal issues include the erosion or subsidence of sediment-starved deltas and delayed responses. The coupling of increased nutrient inputs and decreased sediment loads may promote coastal-zone eutrophication and hypoxia.

◀

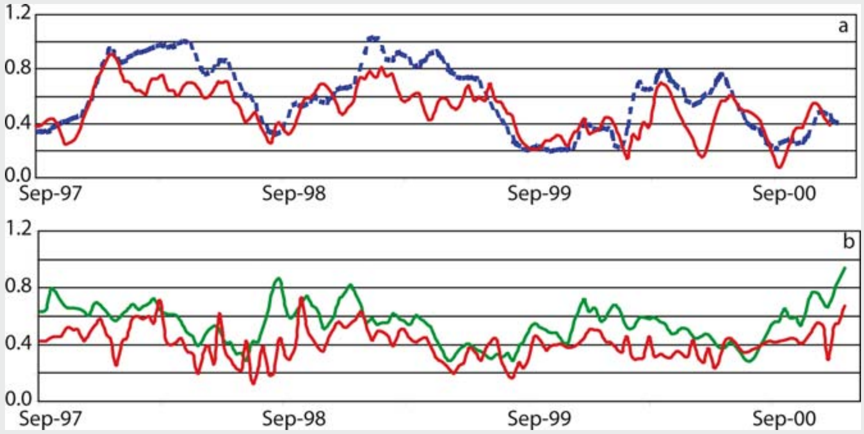


Fig. TB2.8.1. Time-series of the Mississippi River discharge (*blue*), wind stress (*green*) (derived from the National Center for Environmental Predictions, NCEP gridded data) and average sediment concentrations derived from SeaWiFS data (*red*) for two locations. **a** 4 × 4 pixel box located near the mouth of the Mississippi River (see point *A* in Fig. TB2.8.2) where there is a high correlation between discharge and sediment concentration. **b** 4 × 4 pixel box located in a region where there is a high correlation between wind stress and sediment concentration (see point *B* in Fig. TB2.8.3)

Fig. TB2.8.2. Correlation maps for the period 1997–2000 based on 8-day averages of Mississippi River discharge and SeaWiFS-derived sediment data showing region of significant correlation between the Mississippi discharge and the sediment concentration

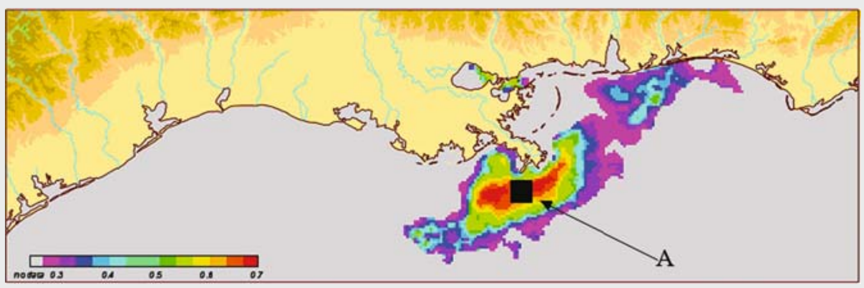
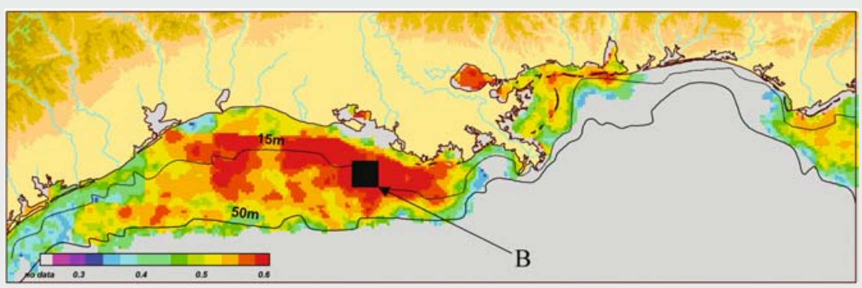


Fig. TB2.8.3. Correlation maps for the period 1997–2000 based on 8-day averages of NCEP-derived wind stress and SeaWiFS-derived sediment data showing a region of significant correlation between the wind stress and the sediment concentration



For society to understand and better manage sediment fluxes a more systematic approach is required (for example, see Text Box 2.8) using new technologies and improving general information. Clearly, there is a need to:

- Assemble existing maps and databases for coastal zone morphology and sediment situations at the global scale. Observations made from this activity could be linked to up-river processes and information about rates of change of documented human impact.
- Establish global maps delineating sediment sources and/or sensitivity to disturbance. This would allow for a better understanding of the effect of change on the system.
- Create an index to encapsulate sediment transit times within basins. This index must be scale-independent as transit times in small river basins are expected to be much shorter than those for larger river basins. This infers that changes occur much more rapidly in smaller basins than in larger ones.
- Determine how long before river loads fill up the terrestrial sediment traps, and what the subsequent impacts will be downstream in the coastal zone. Effort is needed to establish the links between land and ocean.

- Delineate the balance between increasing and decreasing sediment loads due to humans and/or climate change, and the actual and potential impacts.
- Link coastal sediment budgets to terrestrial sediment budgets. This will allow a bridge between the data from upstream gauging stations and the coastal ocean, taking into account the interaction and filtering within estuaries.

2.4 Estuarine Interactions

A tidal inlet system consists of a tidal basin (often in the form of a lagoon) that stores seawater during the flood phase of the tide and exports water mass during the ebb, an entrance channel that links the tidal basin with the open sea, and flood and ebb tidal deltas that are located in the basin and the seaward side of the channel (Hayes 1980, see Text Box 2.9). An estuary typically has three major reaches (Dionne 1963; Fig. 2.12):

a a marine or lower estuary, where processes are dominated by oceanic influence,
b a middle estuary, where mixing of fresh and salt water occurs and density-related processes play a major role, and
c an upper or fluvial estuary, where there is no salt intrusion but tidal effects impact circulation inducing changes in water level and reversing currents.

The "effective tidal limit" is the location in the fluvial reach where tides have a marked influence on the dynamic processes occurring (Perillo 1995).

Boundaries between estuarine reaches are not fixed but change because of variations in the tidal range (e.g., spring-neap cycles, atmospheric forcing) and in river discharge (e.g., high/low runoff). Depending on the dominant factor, the boundaries may move either landward or seaward. Not all estuaries have three reaches. Some estuaries may have only one (e.g., Bahía Blanca estuary in Argentina only has a marine reach as the middle and upper estuaries are within a tributary; the Amazon River in Brazil is mostly a fluvial estuary) or two (e.g., the Negro River estuary in Argentina has only the middle and upper estuaries). Of course the presence/absence of any reach varies with time, most particularly in relation to season.

Most studies of river dynamics and sediment delivery to the coastal zone provide information down to the last gauging station, which is usually located well above the fluvial reach, and the water discharge is calculated as a function of water level. However, there is a relatively

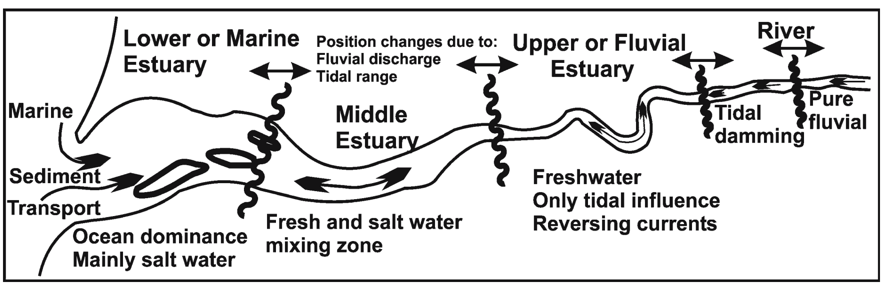


Fig. 2.12. Estuarine processes. Schematic of an estuary and its integration with its river. Boundaries between reaches may change in position depending on river discharge and tidal range (modified from Perillo 1995)

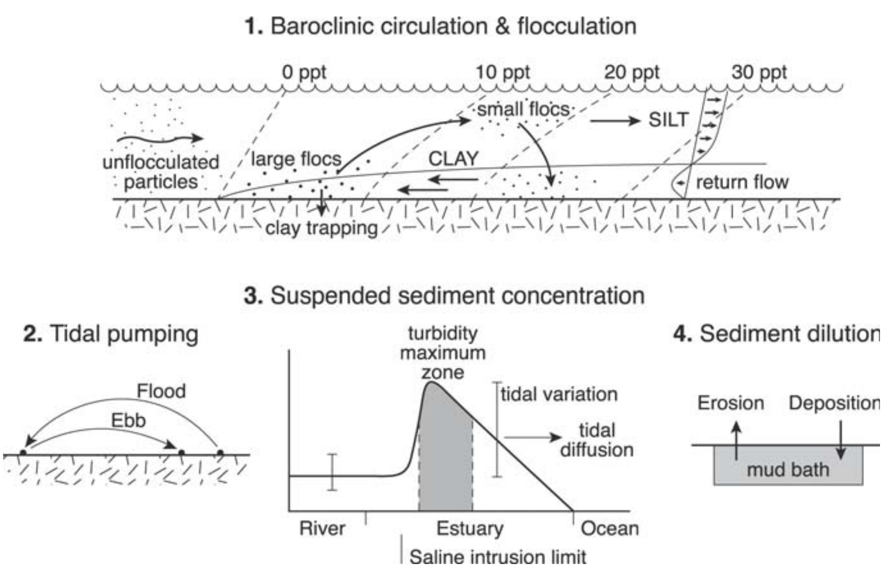


Fig. 2.13. Estuarine processes. Sketch of the key processes generating a turbidity maximum zone in turbid, shallow, macro-tidal estuaries, such as the Fly and Mekong rivers (from Wolanski et al. 1995)

small reach between the upper estuary and the pure fluvial conditions in which changes in water level do occur, but there are no reversing currents: river discharge actually stops for a short period of time. Perillo (2000) defined this reach as *the zone of tidal damming*.

Although the interaction between freshwater and saltwater plays a major role in estuarine dynamics and sediment transport, the geomorphology (shape) of the estuary provides an important control on the interaction between tides and freshwater. Regardless of runoff volume and the tidal range at the mouth, what makes each estuary truly unique is its own particular geomorphology. As the shape of the estuary changes in response to the influences of sediment supply and deposition, current and wave erosion, so will the tidal propagation change with concomitant feedback on the geomorphology.

The Fly River estuary is a prime example of an estuary without river floods that can overwhelm the tidal system and yield freshwater to the mouth of the estuary. In the absence of such floods, the estuary will filter, trap and process the suspended, fine sediment particles. The particles move with the water currents but also have internal motions (Fig. 2.13) that include flocculation, sorting between clay and silt, erosion and settling at tidal frequency, and interaction with the plankton forming muddy marine snow. The particles are sorted in the estuary, clay being preferentially retained (Fig. 2.14) and silt preferentially exported to coastal waters; key processes are the internal circulation in the estuary and the asymmetry between flood and ebb tidal currents. Both processes lead to the formation of a turbidity maximum (Wolanski et al. 1995).

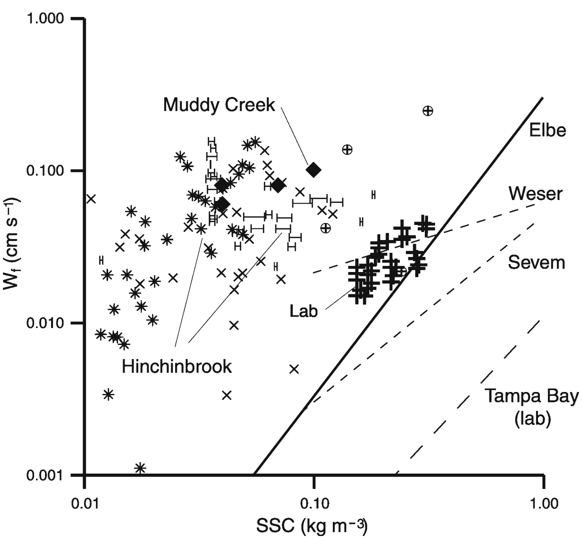


Fig. 2.14. Estuarine processes. Relationship between the suspended sediment concentration (SSC) and the settling velocity (w_f) of fine suspended sediment. Settling velocity values are much higher in tropical (e.g., Hinchinbrook River and Muddy Creek) than in temperate waters (Elbe, Severn and Weser rivers). Laboratory results underestimate the settling velocity because they neglect the formation of muddy marine snow, a dominant process in the field (from Wolanski et al. 2001, adapted from Dronkers and van Leussen 1988)

Some estuaries are filling with sediment that is imported from coastal waters. The Fly River estuary may receive about ten times more sediment from coastal waters than from the river. The imported sediment may be derived from other large rivers nearby which enter the estuary by littoral drift, a process very much dependent on the local, coastal oceanographic conditions and the wind in coastal waters. Such infilling is commonly observed in small estuaries near large rivers. The small Jiaojiang River estuary facing the South China Sea is rapidly infilling (at about 0.13 m yr^{-1}) with fine sediment discharged into coastal waters by the Yangtze River 200 km away (Guan et al. 1998). This infilling requires continuous dredging to maintain navigability. Estuaries along the tropical coast of South America north of the Amazon River mouth are infilling with fine Amazon sediment. In the South Alligator River in tropical northern Australia, much of the infilling material may be pre-Holocene sediment originally deposited along the coast and drowned as sea level rose and the coast retreated at the end of the last ice age. Here, sediment is imported into the estuary ten times faster from the sea than from land runoff, enabling the estuary to keep pace with rising sea levels (Woodroffe et al. 1986, Wolanski and Chappell 1996).

Some tropical, macro-tidal estuaries can be overwhelmed during river flood conditions that can persist for several months where a long monsoon season exists. Alternatively, floods may last only a few days in arid areas subject to occasional major storms such as typhoons. Estuaries respond differently to these contrasting flood regimes. When floods persist for several months, freshwater may extend throughout the estuary to the river mouth. In the Mekong River, the fine sediment is not stored in the estuary, but is discharged directly into shallow, coastal waters, then carried northward and southward along the Vietnamese coast of the South China Sea, the direction of transport depending on oceanography and wind (Wolanski et al. 1996, 1997). Some of that sediment returns to the estuary during the low-flow season. Over time-scales of years, the natural system may be at quasi-equilibrium in the sense that the size, shape and depth of the system may change only very slowly, evolving at time-scales of decades. This is important because it gives humans the time to adapt to changing estuaries and coasts.

In some rivers there is practically no estuary. This can occur when the river discharge is high and the river is sufficiently shallow so that the water is fresh at the mouth. All the riverine sediment is then exported offshore. Examples include the Sepik River in Papua New Guinea, where there is no continental shelf and sediment settles to abyssal depths (Chappell 1993); the Amazon River in

Brazil, where the freshwater discharge and shallow water maintain freshwater to the river mouth, so that sediment is deposited in coastal waters from where it is transported as sand and mud waves along the coast (Nittrouer and DeMaster 1986); and the La Sa Fua River in Guam, where sediment settles over and smothers coral reefs, accumulating for several months (occasionally for one or even two years), before being stirred and flushed out by typhoon-generated waves (Wolanski et al. 2003b).

A sediment equilibrium over time-scales of years may also exist in macro-tidal, semi-arid tropical estuaries. In the Fitzroy River in Western Australia, runoff is very brief and major river floods lasting only a few days are a result of the passage of tropical cyclones (typhoons, hurricanes) (Wolanski and Spagnol 2003). During these few days, the estuary is scoured and fine sediment is exported offshore where it is deposited in coastal waters, to return to the estuary over the rest of the (dry) year as a result of tidal pumping at a rate of 3 000 to 30 000 t d^{-1} (Wolanski and Spagnol 2003). This results in an accumulation of about 0.2–2.0 cm yr^{-1} in the estuary. Estuaries of this type are thus in balance over a time-scale of years, between scouring during rare floods and infilling the rest of year with riverine sediment deposited offshore and entrained back into the estuary.

In the coastal zone, sediment-trapping mechanisms may act individually and collectively, reflecting the interplay of the major dynamic processes (tides, waves, river and groundwater discharge) with the coastal geomorphology (see Text Box 2.9). The shape of the coast determines how tides propagate along the estuary, and the relationship between convergence and friction was used by Le Floch (1961) to classify estuaries. A funnel-shape versus a constant or landward-increasing cross-section (although quite rare) determines whether tidal energy is concentrated or diffused along its pathway. Boundary and bottom roughness elements (e.g., tributaries, intertidal zones, bedforms, sinuosity) dissipate tidal energy. The degree of tidal wave asymmetry and the resulting asymmetry in tidal currents is strongly related to the geomorphological influence on tidal propagation.

Sediment is mostly delivered to the coastal zone by rivers, although the effects of coastal erosion, longshore transport and shore-normal wave and tidal action can be locally important. A large portion of the sedimentary material reaching the coast is retained in estuaries and deltas (see Sect. 2.3.1). The development of an estuary rather than a delta is a function of the relative energy of the river discharge and the dissipative energy of the marine forces (tides and waves) acting on the discharge. This balance seldom reaches equilibrium as both mechanisms are continuously changing across temporal and spatial scales.

A major question presently unanswered for most estuarine systems is their sediment retention. Perillo (2000) proposed a Retention Index (RI) as *the ratio between the sediment permanently retained into the coastal zone to the total sediment input provided by fluvial, marine, atmospheric and even the coastal zone proper*. This retention index considers the long-term residence period, ranging from several years to infinity, and is directly related to the long-term geomorphologic evolution of the coastal zone. Different reaches of an estuary may have different retention indices.

Most estuarine process research is focused on the formation of the turbidity maximum that forms at the landward end of the salt wedge in response to the strong density gradient (Fig. 2.13). Few investigations have addressed the influence of estuarine geomorphology (e.g., presence or absence of tidal flats/marshes/mangroves, tidal channel morphology) and the propagation of the tidal wave along the estuary (e.g., asymmetry of the wave and currents, changes in tidal range) or the interactions between the turbidity maximum and sediment retention in estuaries. Seldom are changes in sediment transport and retention measured along the whole estuary and into the tidal-influenced reaches of the river, nor is their time evolution assessed. Interactions between geomorphology and advection processes are highly nonlinear, making difficult the prediction of the rate of sediment transport and the fate of sediment input into coastal areas.

Flow regulation structures may trap sediment and the estuary may be starved of sediment. The location of the turbidity maximum may then migrate seasonally back and forth in the estuary in response to the seasonally varying freshwater discharge. In many cases, however, the estuary responds by not just a movement in the location of the turbidity maximum, but by changing bathymetry and the location of the coast.

Although natural processes are the major driving mechanisms controlling the dynamics and retention of sediments in estuaries, anthropogenic influences require detailed study. These include river and sediment discharge control produced by damming, irrigation and water pumping, dredging and artificial structures. These procedures not only control circulation, but also change the geomorphology of the reach, inducing modifications in all trapping mechanisms. Furthermore, artificial structures such as harbours, jetties and breakwaters have little or no capacity to adapt to the constant changes in the flow. Seldom, when artificial structures are involved, does the system reach any equilibrium.

2.5 Groundwater Inputs to the Coastal Zone

Although not as obvious as river discharge, continental groundwater also discharges directly into the ocean wherever a coastal aquifer is connected to the sea. Artesian

Text Box 2.9. Physical changes of tidal inlet systems

Shu Gao

Coastal embayments form an important part of the coastal zone, with tidal inlets present in many places along the world coastlines. These systems were formed during the Holocene when sea level rose to inundate low-lying coastal areas. Subsequently, these systems have been affected by wave- and tidally-induced sediment transport and river discharges, and many tidal basins have disappeared due to sediment infilling. For example, 4 400 years BP the Bergen Inlet in the Netherlands was one of the largest inlet systems of the region (Beets et al. 1996). Sediment infilling within the tidal basin ensured that the entire basin was filled by sediment within 1 200 years. Thus, tidal inlets are short-lived features on a geological time-scale.

Infilling of a tidal basin does not always take place at a constant rate. Negative feedbacks, for example changes in time-velocity asymmetry patterns, play an important role in extending the lifetime of a tidal inlet. The tidal currents within the entrance channel are influenced by, among other factors, flood and ebb durations. Generally, a longer flood duration is associated with stronger ebb currents, and a shorter flood duration is related to weaker ebb currents. The former situation is referred to as "ebb dominance" and the latter as "flood dominance". What factors control these difference patterns? Speer and Aubrey (1985) identified two parameters responsible for the difference: the tidal range (R) to water depth (H) ratio for the entrance channel, and the intertidal zone area (A_0) to the total area (A) ratio for the tidal basin. A large R/H ratio favours flood dominance, while a large A_0/A ratio favours ebb dominance. From this it may be inferred that at an early stage of tidal inlet evolution, flood dominance is most probable because the R/H ratio tends to be large and the A_0/A ratio small, resulting in intense sediment transport into the tidal basin. Infilling of sediment increases the intertidal zone area and scouring of the channel increases the channel depth. Thus, the R/H ratio is reduced and the A_0/A ratio is enhanced. Eventually, ebb dominance will replace flood dominance, with a consequent reduction in the rate of sediment infilling. This negative feedback mechanism explains why most present-day inlet systems are ebb-dominated.

More complicated inlet behaviours with regard to time-velocity asymmetry patterns have been observed (Jia et al. 2003). Yuehu is a small inlet system with a tidal basin 5 km^2 in area, lying in the eastern part of Shandong Peninsula, China. The inlet system was largely un-impacted before the late 1970s when, for aquaculture purposes, the entrance to the lagoon was artificially closed and some of the intertidal areas were reclaimed. As a result, the inlet system now experiences a smaller flood duration. However, the tidal currents show complex patterns (Fig. TB2.9.1), which may be attributed to regional tidal characteristics and local entrance channel geometry. For example, the shape of the entrance channel is such that the cross-sectional area changes rapidly at certain water levels, altering the tidal currents. Because changes in tidal-inlet geomorphology will cause the coastal zone to change in terms of material cycling and ecosystem evolution, it is important to understand the processes and behaviours of tidal inlet systems. In particular, the negative feedbacks described above may be used to prolong the lifespan of these coastal systems.

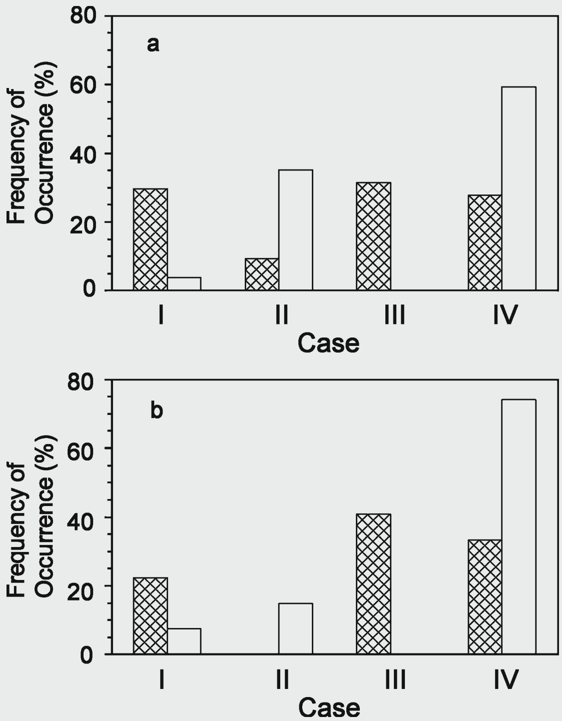


Fig. TB2.9.1. Frequency of occurrence for different time-velocity asymmetry patterns associated with the Yuehu inlet system, eastern China: (**a**) winter 1998 and (**b**) summer 1999. Case I – flood duration is shorter than ebb, and flood current velocity is larger than ebb. Case II – flood duration is longer than ebb, and flood current velocity is smaller than ebb. Case III – flood duration is longer than ebb, and flood current velocity is larger than ebb. Case IV – flood duration is shorter than ebb, and flood current velocity is smaller than ebb. The *shaded bars* denote cross-sectional mean currents, the *blank bars* vertically averaged tidal currents at the entrance center

aquifers can extend for considerable distances from shore underneath the continental shelf, with discharge to the ocean at their points of outcrop. In some cases, these deeper aquifers may have fractures or other breaches in the overlying confining layers, allowing groundwater to flow into the sea. Although submarine springs and seeps have been known for many years (written accounts exist from at least the Roman period), these features have traditionally been perceived as hydrological "curiosities" rather than objects for serious scientific investigation (Kohout 1966).

Within the last few decades, recognition has emerged that, at least in some cases, groundwater discharge into the sea may be both volumetrically and chemically important (Johannes 1980). It is now widely recognised that there are several oceanic processes that drive advective flow or re-circulated seawater through permeable sediments in addition to fresh groundwater flow driven by hydraulic gradients on land. The terrestrial-driven and ocean-derived flows grade into each other, especially near the coast. It is important to have a nomenclature that is compatible to both types of flow.

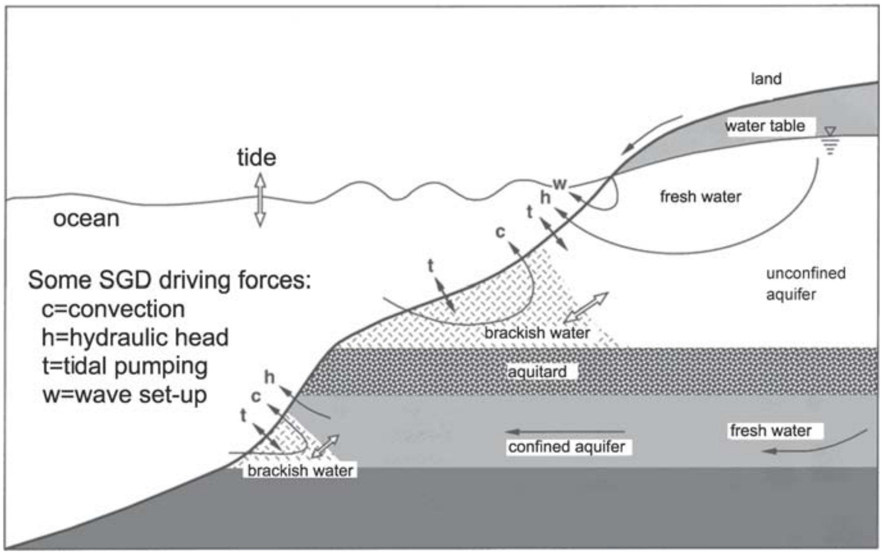


Fig. 2.15.
Submarine groundwater flux. Nomenclature of fluid exchange and schematic depiction (no scale) of processes associated with submarine groundwater discharge. *Arrows* indicate fluid movement (from Burnett et al. 2003, modified from Thibodeaux and Boyle 1987)

2.5.1 A New Understanding

The most general and frequently cited definition of groundwater is water in the saturated zone of geological material (e.g., Freeze and Cherry 1979). Water in the pores of submerged sediments or rock is, therefore, properly "groundwater" since the geological material below the sea floor will be saturated. As a result, "submarine groundwater discharge" (SGD) is any and all flow of water out across the sea floor (Fig. 2.15). SGD is defined without regard to its composition (e.g., salinity), origin or phenomena driving the flow. Where the sediments are saturated, as they are expected to be in all submerged materials, "groundwater" is synonymous with "porewater."

Traditional hydrology has been concerned with terrestrial groundwater. As a result, groundwater has been defined as rainwater that has infiltrated and percolated to the water table, or similar definitions consistent with the applications to freshwater, terrestrial systems (e.g., Considine 1995). Such qualifications on the definition of groundwater lead to conceptual problems when dealing with submarine discharges. SGD does not have to be terrestrially derived, although it can be and is in many prominent situations. When SGD is measured, there is seldom a way to evaluate its source. While it may be legitimate to require water classified as "groundwater" to move according to Darcy's Law, even that may be too restrictive in some highly channelised (e.g., karst) situations. At least one definition of groundwater explicitly excludes underground streams (Wyatt 1986) while another specifically includes them (Bates and Jackson 1984; Jackson 1997). Since karst is such an important setting for SGD, we include such features.

In the marine environment, submarine groundwater recharge (SGR) also occurs as tides, waves, currents, sea-level fluctuations and density differences force seawater into the sea floor. This water eventually must leave the aquifer. Recycling of ocean water has been referred to, in various articles, as "irrigation" or "ventilation" or "transportation," terms usually applied to the surficial layers within a meter or so of the sea floor (e.g., Conley and Inman 1994). In some cases, the recharged waters are discharged locally. In other cases, waters can emerge far from the source, even sub-aerially as in saline springs in Hawaii (Cooper et al. 1964).

SGD can vary widely over time and space. Stirring or agitating of porewater by short-period water-waves, without necessarily producing any net flow has been referred to as "wave pumping" or "wave stirring" (e.g., Harrison et al. 1983, Riedl et al. 1972). "Floating" (Thorstenson and MacKenzie 1974) or "salt fingering" (Gorsink and Baker 1990) describe the situation when, if the density of the ocean water increases above that of the porewater for any reason, porewater can float out of the sediment by gravitational convection in an exchange with denser seawater, again without a net discharge. SGD has also been referred to as "flushing." Flushing generally involves a continuous replacement of porewater driven by the hydraulic gradients ashore or pressure gradients in the coastal ocean. Gradients may be due to wave set-up at the shore (Li et al. 1999), tidal pumping at the shore (Nielsen 1990), or differences in tidal elevations across narrow reefs or barrier islands (Bokuniewicz and Pavlik 1990, Reich et al. 2002).

The system of terminology developed by the SCOR Working Group 112 (Burnett et al. 2003) is illustrated in Fig. 2.16. The flow of water across the sea floor can be divided into SGD, a discharging flow out across the sea floor, or SGR, a recharging flow in across the sea floor. The two terms do not have to balance because SGD can, and often will, include a component of terrestrially re-

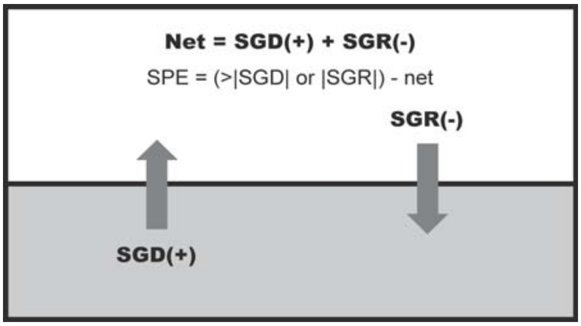


Fig. 2.16. Submarine groundwater flux. Submarine groundwater discharge (SGD) comprises any fluid flow upward (+) across the sea floor while submarine groundwater recharge (SGR) is fluid flow into (–) the seabed. The "net" flow is the mathematical sum of these two components that do not necessarily balance. Submarine porewater exchange (SPE), analogous to the mixing parameter in the LOICZ biogeochemical budget terminology, is the larger absolute value of SGD or SGR minus the net flow. This assumes that the domain of the SPE remains constant

charged water. Alternatively, some or all of the SGR can penetrate the sub-aerial aquifer, raising the water table or discharging as terrestrial surface waters (e.g., saline springs) rather than discharging out across the sea floor. The net discharge is the difference between these two components. The "submarine porewater exchange" (SPE) is the difference between the larger of the two (SGD or SGR) volume fluxes and the net. In other words, SPE is the smaller absolute value of either SGD or SGR. SPE is equivalent in magnitude to V_x (a mixing term) in the LOICZ biogeochemical budget convention (Gordon et al. 1996, see Chap. 3). By that convention, V_x is positive for flows into the sediment.

SGD may consist of multiple components. One is meteoric water that had fallen on dry land as atmospheric precipitation, infiltrated the soil on rock, and percolated to the water table. It can be driven across the sea floor by the onshore hydraulic gradients although it is possible that this exchange takes place as gravitational convection, i.e., buoyant fresh porewater "floating" across the sea floor into the open, salt water. Another important component of SGD may be re-circulated seawater that can also be driven in part by hydraulic gradients on land as well as by various oceanic forces. In some cases, SGD can also contain saline connate groundwater or groundwater whose salinity has been raised by dissolution of salt within the aquifer itself. While it is tempting to subdivide SGD in the terminology according to its principal components, i.e., fresh water and saline water, we have elected not to do this, as it could lead to somewhat arbitrary decisions when mixtures of fresh and salt waters are encountered.

SGD could be classified based on the driving forces. Terrestrial hydraulic gradients and the consequent motion of the meteoric groundwater can drive the seepage of infiltrated seawater. SGD could be driven by any of a number of oceanic processes, such as wave pumping, wave set-up or set-down and tidal pumping. A third class of endogenic drivers such as thermal gradients, osmotic pressures, inverted density stratification or consolidation must also be considered. Although such divisions are useful in our efforts to understand the mechanisms involved, they cannot serve as a primary basis for classification and terminology because we rarely have sufficient information to define the driving forces when field measurements are made. Furthermore, it should be recognised that these forces do not necessarily operate in isolation, i.e., flow through coastal sediments may represent a composite of terrestrial and marine forces and components.

Although our broad definition of SGD allows inclusion of such processes as deep-sea hydrothermal circulation, fluid expulsion at convergent margins and density-driven cold seeps on continental slopes, we have restricted the scope of our discussion to fluid circulation through continental shelf sediments with emphasis on the coastal zone.

2.5.2 Advective Porewater Exchange

As discussed above, the flow of water from coastal sediments is not exclusively tied to terrestrially driven (fresh) groundwater seepage. Interaction between boundary layer currents and sea-bed topography causes advective porewater flows in permeable coastal sediments that are not as conspicuous as submarine springs but can be an important mechanism controlling the geochemical characteristics of the water column in the coastal zone (Shum and Sundby 1996, Boudreau et al. 2001).

The lower permeability limit for porewater transport that significantly exceeds diffusive transport is approximately 10^{-12} m^2 (Huettel et al. 1996). In general, the mean grain size and the permeabilities of the sediment surface layers increase from the continental rise towards the coast (Emery and Uchupi 1972). The decrease in water depth amplifies the effect of bottom currents; at water depths < 100 m, the wave orbital motion reaches the sea bed and tidal current speeds increase, producing strong bottom shear and sediment erosion (Nittrouer and Wright 1994, Jing et al. 1996). In this zone, frequent resuspension of terrigenous shelf deposits and removal of the fine material by cross-shelf currents result in well-sorted sand beds that are characterised by high permeabilities that permit measurable porewater flows.

In the upper part of the continental slope, most of the 10^{-12} m^2 permeability isolines turn parallel to the 200 to 500 m isobaths (Riedl et al. 1972). The contribution of the porous component to the surface sediments of the shelf of the eastern USA is about 92% (gravel 11%, shell 14%, sand 67%; Hayes 1967, Stoddart 1969, Riedl et al. 1972).

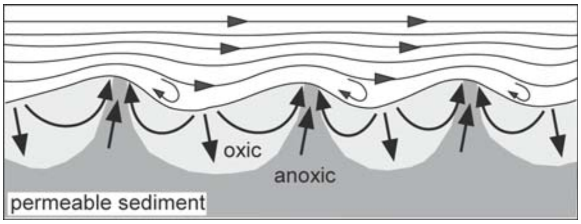


Fig. 2.17. Submarine groundwater flux. Schematic view of porewater flow directions under ripples exposed to unidirectional flow. Water intrudes the sediment at the upstream face of the ripple and moves on a curved path to the downstream slope where it is released from the sediment (from *http://www.scor-wg114.de/*)

The area of higher permeability sand sediments on an average shelf may be about 65%, in agreement with the estimates of Emery (1968).

Where bottom currents are sufficiently strong to resuspend and winnow sediment, the seabed surface is structured by ripples (Wiberg and Harris 1994) that cause the advective porewater exchange. The deflection of the unidirectional or oscillating boundary-layer currents at sediment surface structures (e.g., ripples, biogenic topography), produces local pressure gradients that drive porewater flows and interfacial fluid exchange (Webb and Theodor 1968, Thibodeaux and Boyle 1987).

In surface depressions (ripple troughs) water penetrates into the sediment and flows on a curved path towards protruding surface structures (the ripple crests), where the porewater is released (Huettel and Gust 1992; Fig. 2.17). For reasons of mass balance, the same volume of water that is forced into the sediment also flows from the bed. The resulting porewater circulation carries organic matter and oxygen to the sediment, creates horizontal concentration gradients that can be as strong as the vertical gradients, and increases the flux of porewater constituents across the sediment-water interface. Due to the continuously changing sediment topography and boundary-layer flow characteristics, advective porewater circulation and ensuing biogeochemical zonation are highly variable in space and time (Huettel et al. 1996).

The depth of the sediment layer that is affected by this advective exchange is related to the size and spacing of the ripples and, in homogeneous sediment, reaches down to approximately two times the ripple wavelength (Hutchinson and Webster 1998). Under calm hydrodynamic conditions (friction velocity, $u^* < 5$ cm s^{-1}), the porewater velocities in typical shelf sands (200 µm, permeability, $k = 10^{-11}$ m^2) may reach vertical velocities of 2 to 3 cm h^{-1} in the uppermost centimeter of a rippled bed (5 cm amplitude, 30 cm wavelength; Huettel et al. 1996). With these upwelling velocities, the sediment exposed to unidirectional flow (e.g., during receding tide) releases approximately 75 to 100 L m^{-2} d^{-1}. In flume experiments, surface gravity waves caused porewater release rates up to 222 L m^{-2} d^{-1} in similar sediments, demonstrating that oscillating boundary flows can effectively enhance the fluid exchange between the seabed and the water column.

Riedl et al. (1972) measured interfacial porewater exchange caused by surface gravity waves using thermistor flow sensors embedded in permeable shelf sands. They calculated that worldwide the waves filter a volume of 97×10^3 km^3 yr^{-1} through the permeable shelf sediments. The intertidal pump, driven by swash and tidal water level changes, moves another 1.2×10^3 km^3 yr^{-1} through the sandy beaches of the world. These estimates suggest that wave action filters the total ocean volume through permeable sediments within 14 000 years.

2.5.3 Magnitude of Submarine Groundwater Discharge

There are many factors that affect rates of fresh groundwater flow into the coastal zone, either directly or indirectly. Driving force and transmissivity are the main factors that determine the flux of terrestrially-derived SGD. The driving force is a function of the hydraulic gradient (influenced by topography) and the terrestrial groundwater recharge rate (affected by precipitation and evapo-transpiration). The types and extent of vegetation as well as climate will determine evapo-transpiration rates. Transmissivity may be controlled by permeability (geology) and development of river systems (geomorphology). Thus, parameters related to geology, precipitation, vegetation (land use) and topography are all contributing factors in determining rates of fresh groundwater flow to the sea.

Without the benefit of measurements, one may predict that land-derived SGD fluxes would be high in areas of high permeability (karst), high relief near the coast, areas without well-developed river systems (some large oceanic islands), and regions with high groundwater recharge rates (humid tropics). To evaluate the importance of groundwater pathways to the coastal zone, direct assessments are required by modelling, direct measurements, geochemical tracers or other approaches (Burnett et al. 2001, Burnett et al. 2002, Burnett et al. 2003).

SGD estimates have been made for many independent studies performed on the east coast of the United States, in Europe, Japan and Oceania (Taniguchi et al. 2002). Some studies have been done on the west coast of the US and in Hawaii. A summary of estimated and measured fluid discharges to the ocean and across the seabed shows that while unit fluxes are small, total discharge values can be huge (Table 2.3). Many SGD measurements have been made in karst areas where the hydraulic conductivity of the aquifers is large, and thus significant amounts of fresh groundwater discharge are expected under reasonable hydraulic gradients.

Table 2.3. Submarine groundwater flux. Fluxes of terrestrially-derived water and seawater to the coastal zone and ocean expressed as volumetric discharge per unit time, flux per unit length of shoreline, and unit area fluxes

Flux	Fluid composition/origin[a]	Reference
Global discharge ($km^3\ yr^{-1}$)		
Rivers = 37 400	Fresh/terrestrial	Berner and Berner (1987)
Fresh groundwater seepage = 2 200[b]	Fresh/terrestrial	Zekster (2000)
"Intertidal pump" = 1 170	Composite/mixed	Riedl et al. (1972)
"Subtidal pump" = 95 700	Seawater/marine	Riedl et al. (1972)
Shoreline fluxes ($m^3\ m^{-1}\ day^{-1}$)		
Rivers = 170	Fresh/terrestrial	Calculated using shoreline length[c] = 600 000 km
Groundwater seepage = 10	Fresh/terrestrial	Calculated from Zekster (2000)
Measured (Florida) = 3–35	Composite/mixed	Cable et al. (1997), Burnett et al. (2002)
Measured (Perth) = 2–8	Composite/mixed	Burnett and Turner (2001)
Unit fluxes ($m^3\ m^{-2}\ yr^{-1}$)		
Seepage meters = 5–100	Composite/mixed	Calculated from Taniguchi et al. (2002)[d]
Subtidal pump = 3.5	Seawater/marine	Riedl et al. (1972)

[a] Composition refers to fresh (or meteoric) water, seawater or a mixture; "origin" refers to driving force, either terrestrial hydraulic gradients or marine forcing (tidal pumping, wave set-up) or a mixture of terrestrial and marine.
[b] Estimates for the freshwater component of groundwater discharge to the ocean vary tremendously, from values of 100 $km^3\ yr^{-1}$ (COSOD II 1987) to ~4 000 $km^3\ yr^{-1}$ (Garrels and MacKenzie 1971). The value cited here represents ~6% of the river flow.
[c] The length of a shoreline depends upon the resolution of the measurement interval so there are no definitive values (see Text Box 1.1, Chap. 1). Estimates between about 500 000 and 600 000 km appear reasonable for global shoreline lengths. Zekster (2000) stated that "… a shoreline length of 600 000 km excludes Antarctica, Greenland, the Arctic and some permafrost regions."
[d] Approximately 85% of the measured seepage values from the coastal zone in this compilation fall in this range (1–30 cm day^{-1}).

2.5.4 Biogeochemical Implications

The advective flux of terrestrially-driven groundwater through coastal sediments is becoming recognised as an important mechanism for transferring material from the land to the ocean (Cathles 1990, Valiela et al. 1990, Moore 1996, Jickells 1998). Flow may occur through the surficial aquifer or through breaches in deeper semi-confined coastal aquifers (Moore 1999). This process may affect the biogeochemistry of estuaries and the coastal ocean through the addition of nutrients, metals and carbon (Moore 1996).

Most geochemical studies of sediments have concentrated on muddy sites where diffusion and biological mixing drive exchange with the overlying ocean. The techniques and models used in those studies are not applicable to sites where advection through permeable sediments is the primary exchange agent. Results based only on muddy areas may seriously underestimate the fluxes of biogeochemically important materials in the coastal ocean.

During the passage of terrestrially-derived fluids through the sediments, mixing of seawater with fresh groundwater and chemical reactions of the fluids with solid phases may occur. The emerging fluid is chemically distinct from the groundwater and seawater end-members. Concentrations of nutrients, trace metals, organic carbon, methane and CO_2 may be considerably higher than surface ocean waters (Simmons 1992, Bugna et al. 1996, Paerl 1997, Cai and Wang 1998). Major ions may be affected by diagenesis of solid phases (Burt 1993). Because SGD may bypass the estuary filter, this source term may affect the coastal ocean quite differently from river discharge.

In these coastal aquifers or "subterranean estuaries" (Moore 1999), chemical reactions between the mixed waters and aquifer solids modify the fluid composition much as riverine particles and suspended sediments modify the composition of surface estuarine waters. The importance of chemical reactions between aquifer solids and a mixture of seawater and fresh groundwater is well-recognised by geochemists (Runnels 1969, Back et al. 1979). For example, mixing of seawater supersaturated with calcite and fresh groundwater saturated with calcite can result in solutions that are either supersaturated or undersaturated (Plummer 1975). This mechanism explains the massive dissolution of limestone along the northern Yucatan Peninsula (Back et al. 1979). Dissolution of submarine limestone by groundwater flow creates distinctive canyons and escarpments on continental margins (Paull et al. 1990).

Calcite dissolution may also be driven by addition of CO_2 to fluids in the subterranean estuary. Salt water penetrating the Floridian aquifer near Savannah, Georgia, is enriched in inorganic carbon and calcium, as well as ammonium and phosphate, relative to seawater and fresh groundwater end members, due to oxidation of organic carbon within the aquifer or CO_2 infiltration from shallower aquifers (Burt 1993). Shallow coastal groundwaters are highly supersaturated with respect to CO_2 (Cai and Wang 1998).

Groundwater may be an important source of nutrients for coral reefs (Marsh 1977, D'Elia et al. 1981, Crossland 1982, Umezawa et al. 2002) or other communities on the continental shelf (Johannes 1980, Simmons 1992, Jahnke et al. 2000). The fluxes of nitrogen and phosphorus to the Georgia and South Carolina shelf from SGD have been estimated to exceed fluxes from local rivers (Simmons 1992; Krest et al. 2000).

Groundwater-borne nutrients can have significant effects on water quality in surface estuaries (Reay et al. 1992). Groundwater may have nutrient concentrations several orders of magnitude greater than surface waters either via contamination (e.g., from septic systems) or natural processes. Thus, nutrient concentrations in coastal groundwater, which are modified by man-made changes to coastal regions, may be a significant factor in the eutrophication of nearshore waters (Valiela et al. 1990).

The ecological significance of the advective porewater flow beyond the zone of influence of SGD derived from land is fundamentally different from that of the terrestrially-derived groundwater inputs, as there is no import of allochthonous substances into the coastal zone. Nevertheless, advective porewater transport may be important for the coastal cycles of matter through the acceleration of the deposition and mineralisation process (Marinelli et al. 1998). Due to advective porewater exchange, coastal permeable sands function like expansive biocatalytic filter systems and may in part be responsible for the tight cycling of matter in shelf waters, reducing the export to the deep ocean (Huettel et al. 1998).

Flume studies have shown that with interfacial water flows, suspended particles and phytoplankton are filtered from the water column, thereby increasing the deposition rate (Huettel and Rusch 2000). Within the sediment, the organic particles are exposed to higher mechanical stress, higher bacterial abundances and higher exo-enzyme concentrations, which accelerates their decomposition. Directed advective transport of oxygen and other electron acceptors into the sediment (Lohse et al. 1996, Ziebis et al. 1996) and simultaneous transport of decomposition products (e.g., HCO_3^-, inorganic nutrients) out of the sands (Gehlen et al. 1995, Huettel et al. 1998) further enhance the sedimentary degradation and convert the permeable sands into efficient bioreactors (Huettel and Rusch 2000).

The effect of advective porewater flow from the biocatalytic sand filter is documented by high benthic primary production on coarse organic-poor sands reaching 800 mg C m^{-2} d^{-1}. About 30% of the continental shelf sea floor (3.4×10^8 km^2) receives sufficient light to support significant rates of benthic primary production that would result in an estimated production of 2.9×10^{14} g C yr^{-1} (~0.3 Gt C yr^{-1}; Nelson et al. 1999, Jahnke et al. 2000). However, this indirect evidence for advective nutrient release may be strongly affected by the impact of nutrient-rich terrestrially-derived groundwater through the sandy seabed. Investigations using isotopes and other novel techniques are needed to assess the contribution of the two processes to benthic primary production. How these advective processes affect the biogeochemistry of estuaries and the continental shelf is only beginning to be appreciated.

Much work remains before SGD can be evaluated relative to more conventional processes. For example, nutrients may enter the coastal ocean through rivers, the atmosphere and upwelling at the shelf break, as well as in SGD. The biological effects of these inputs depend not only on the magnitude of the input but how and where the nutrients are delivered. A relatively small input to an isolated estuary may have an effect much different than a more substantial input spread over a large fraction of the shelf. Differing amounts of delivered nitrogen, phosphorus and silica may also create distinct responses. To achieve a more complete understanding of the role of advective processes in sediments, studies over a range of scales and environments are required.

2.6 Influence of Human Activities on Material Fluxes

The stability of the coastal zone is affected by the influence of humans on upland water resources through marked changes in timing, flux and dispersal of water, sediments and nutrients. Although there are numerous large construction projects that exemplify the impact of humans at the local scale, one example is highlighted here: the building of an artificial island off Hong Kong (see Text Box 2.10). Below we limit our discussion to more global issues.

2.6.1 The Role of Dams and Other Land Transformations

Massive anthropogenic transformations of the Earth's surface during the 20th century have begun to impact continental-scale patterns of river runoff, sedimentation and coastal erosion, ultimately affecting global sea-level rise (Gornitz 2001). Sequestration of water in reservoirs and artificial lakes diminishes the outflow of water to the sea. Conversely, groundwater mining, deforestation and urbanisation increase the volume of water delivered to the oceans. Groundwater mining or overdraft – the withdrawal of groundwater in excess of natural recharge rates – is becoming a significant problem in many arid parts of the world. Although a large fraction of this water is used consumptively (i.e., evaporated, transpired or otherwise utilised by humans, animals or plants), the balance runs off and augments stream flow. Removal of the natural vegetation cover for agriculture and urbanisation also increases runoff in the short-term, due to reduced soil infiltration and expansion of impermeable land surfaces. These land-use changes are often accompanied by enhanced soil erosion, which lead to increased sedimentation rates in reservoirs.

Human activities reduce global river runoff by ~328 $km^3 yr^{-1}$, shifting the balance toward greater storage of freshwater on land (Gornitz 2001). This cutback is slightly less than 1% of the total yearly volume of water delivered by rivers to the oceans (42 650 $km^3 yr^{-1}$) and around 8% of the yearly volume of human utilisation of freshwater resources (3 414 $km^3 yr^{-1}$). The volume of water sequestered on land each year lowers sea level by around 0.9 mm yr^{-1}. This rate is of comparable magnitude but opposite in sign to the observed sea-level rise of 1–2 mm yr^{-1} (Houghton et al. 2001). These estimated impacts on sea-level rise are only approximate, due to insufficient data and a number of simplifying assumptions. In the near future, satellite imaging, radar altimetry and gravity measurements will monitor the global water mass budget and quantify anthropogenic transformations.

Between 4510 and 5330 km^3 of water – 10.6% to 12.5% of the total annual river runoff (42 650 $km^3 yr^{-1}$) – is presently stored behind large dams. More than 90% of this reservoir capacity has been created since the 1950s (Fig. 2.18). Siltation reduces the storage capacity of reservoirs, which in turn decreases the volume of water that otherwise would have been withheld from sea-level rise. Although some Asian reservoirs are filling at the rate of 2% per year, a sampling of siltation rates from many dams around the world suggests an average value of around 1% per year. Siltation has decreased the storage capacity by as much as 45.1 to 53.3 km^3, or 1.13–1.33 $km^3 yr^{-1}$ since the 1950s, representing an average increase in sea level of 0.003 to 0.004 mm yr^{-1} (Gornitz 2001). Although negligible in terms of sea-level change, siltation considerably shortens the useful life span of the reservoir and curtails sediment delivery to many coastal regions, such as Louisiana, USA and the Nile Delta, Egypt, resulting in severe erosion (see Sect. 2.3.2.4).

The average rate of relative sea-level rise in Louisiana is around 10 mm yr^{-1} – approximately 5 to 10 times the global mean value. This high rate is largely due to natural land subsidence, caused by sediment loading and compaction in the vicinity of the Mississippi River delta. Submergence due to the high rates of relative sea-level rise may contribute, in part, to the severe erosion of barrier islands and coastal wetland losses of nearly 100 $km^2 yr^{-1}$. However, damming of upstream tributaries and other flood control measures have cut the sediment load of the Mississippi River by 46% since the 1900s (Wells 1996). The reduced sediment supply to the delta is insufficient to compensate for the high subsidence rates, and thus the shoreline is rapidly retreating.

2.6.2 Ecosystem Health and Diversity

Rivers deliver reactive nutrients as a dissolved load and these nutrients (and associated metals) are consumed by the primary producers (e.g., bacteria, phytoplankton). For higher latitude rivers, there is a synchronicity between the spring freshet, which delivers and spreads this freshwater-derived material into the coastal zone, and the onset of heightened solar radiation, needed for the formation of a plankton bloom. Zooplankton productivity is intimately tied to the timing of these fluxes and the formation of the plankton bloom. However, since higher latitude climes need increased electrical power production, both in winter (for urban heat production) and in summer (air conditioning demands), freshet water is stored in large reservoirs and released through the year based on seasonal demands. Consequently, food-web composition can be greatly affected.

The importance of suspended materials to plankton is due to three characteristics of the particles (Lewis and Syvitski 1983): (*a*) they react with dissolved materials such

Fig. 2.18.
Water fluxes. Distribution of the world's major dams. Between 10.6% and 12.5% of the total annual river runoff (42 650 $km^3 yr^{-1}$) is presently stored behind large dams, mostly created since the 1950s

Text Box 2.10. Construction of the new Hong Kong International Airport

Wyss W.-S. Yim

Anthropogenic activity in the coastal zone is accelerating land-ocean interaction at an unprecedented rate through land reclamation from the sea for major infrastructures. One example is the recently completed Hong Kong International Airport with a total land area of 12.48 km^2 located just south of the Tropic of Cancer on the inner continental shelf of the northern South China Sea (Fig. TB2.10.1). Table TB2.10.1 shows some statistics for the airport.

The site of the new Hong Kong International Airport lies immediately south of the Pearl River delta front within the Pearl River Estuary (Fig. TB2.10.1). An island platform was created for the airport by levelling two islands (Chek Lap Kok and Lam Chau) with a total area of 3.1 km^2, and reclaiming a further 9.38 km^2 from the sea. For investigating the ground conditions, about 2 000 boreholes and over 5 000 cone penetration tests were made, providing a vast geo-technical database (Anon 1996). Offshore site preparation involved dredging the seabed to completely remove the soft marine clay of Holocene age and to partially remove the comparatively stiff marine clay of Last Interglacial age, to depths ranging approximately from 4 to 30 m below mean sea level. A complete and thick sequence of unconsolidated Quaternary deposits occurs to the west of Lam Chau, and include:

1. Marine unit 1 (M1) of Holocene or oxygen-isotope (OI) stage 1 age with abundant shells and shell fragments (Yim and Li 1983) radiocarbon dated at no older than 8 200 years BP (Yim 1999) post-dating the meltwater pulse of the Laurentide icesheet.
2. Terrestrial unit 1 (T1) of last glacial to pre-last interglacial or OI stage 2–4 age.
3. Marine unit 2 (M2) of last interglacial or OI stage 5 age with rare shell fragments because of post-depositional groundwater dissolution (Yim and Li 1983). Oyster shells found elsewhere in Hong Kong from the same unit have yielded a uranium-series age of about 130 000 years BP (Yim et al. 1990).
4. Terrestrial unit 2 (T2) of second last glacial or OI stage 6 age.

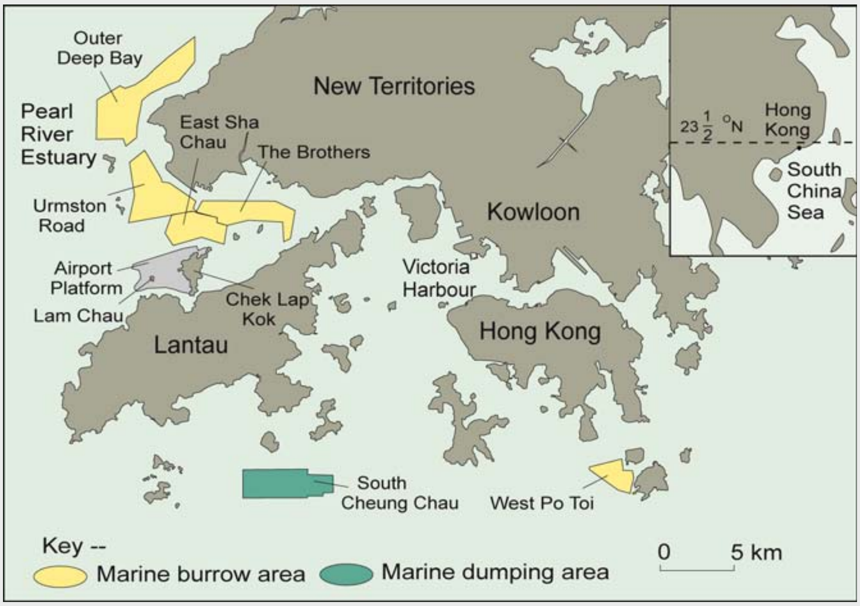


Fig. TB2.10.1. Location map of the Hong Kong International Airport, marine borrow areas and mud disposal areas

Table TB2.10.1. Some statistics of the new Hong Kong International Airport

Date of opening of airport	July 6 1998
Construction time of airport island	42 months
Total cost of site preparation	US$1.16 billion
Total area of airport	12.48 km^2
Total area reclaimed from the sea	9.38 km^2
Dimensions of two runways	Length 3.8 km, width 60 m, 1.525 km apart
Volume of marine clay dredged	68.8 million m^3
World's dredging fleet	75%
Volume of overburden removed from marine burrow areas to exploit sand	40 million m^3
Volume of sand brought in from marine burrow areas for reclamation	76 million m^3
Total volume of fill	197 million m^3
Minimum dredged level	3 m below Principal Datum
Maximum dredged level	29 m below Principal Datum
Total length of seawall	13 km

◀

5. Marine unit 3 (M3) of second last interglacial or OI stage 7 age.
6. Terrestrial unit 3 (T3) of third last glacial or OI stage 8 age, thermo-luminescence dated at about 250000 yearsBP (Yim et al. 2002).
7. Marine unit 4 (M4) of third last interglacial or OI stage 9 age. Oyster shells found elsewhere in Hong Kong from the same unit have yielded a uranium-series age of 308 000 years BP (Yim and Choy 2000).
8. Terrestrial unit 4 (T4) of fourth last glacial or OI stage 10 age.
9. Residual soil pre-dating fourth last glacial or OI stage 10 age.

In other Hong Kong waters, a maximum of 5 marine units and 5 terrestrial units has been observed, in agreement with the 5 interglacial-glacial cycles of the Vostok ice core in Antarctica (Petit et al. 1999).

Between the islands of Chek Lap Kok and Lam Chau (Fig. TB2.10.1), a paleosol referred to as a paleo-desiccated crust by Tovey and Yim (2002) is well developed on top of the M2 unit. This crust was formed by acid-sulfate soil development through the oxidation of pyrite present. Because the crust was indurated by iron-oxide cementation, its removal by dredging was found to be difficult. West of Lam Chau, older palaeosols with crusts showing greater induration than the top of the M2 unit are found on top of the M3 and M4 units reflecting the ageing effect under terrestrial conditions. Sea-level and paleo-environmental changes determined the engineering properties of the "M" and "T" units (Yim and Choy 2000). Within the reclamation, the greatest ground settlement was found in areas where the cumulative thickness of "M" units left in place is the greatest. Figure TB2.10.2 shows a three-dimensional model of the post-dredging ground surface within the area of the airport platform.

For land reclamation, sand was imported from six marine borrow areas within Hong Kong waters, while muds dredged both from the airport site and the marine borrow areas were disposed in an offshore dumping area south of Cheung Chau (Fig. TB2.10.1). The bulk of the sand mined from the marine borrow areas for reclamation pre-date the OI stage 5 and were formed during low sea-level stands under terrestrial conditions (Yim 2001). Figure TB2.10.3 shows a trailing suction hopper dredger similar to the type used for the reclamation of the airport and Fig. TB2.10.4 shows the partially completed airport platform in 1995.

Construction of the Hong Kong International Airport has had considerable impact on the coastal environment (ERL Asia Limited 1982). The rate of change during the 42-month construction period of the airport platform exceeded that of any natural processes. Of the impacts, the most important ones included:

- sediment removal from the seabed of the inner continental shelf and their redistribution,
- destruction of the natural shoreline and its replacement with a seawall,
- loss of coastal habitats,
- changed coastal hydrology through the creation of the airport platform, and
- increased loading on the earth's crust through the placement of construction materials on the platform.

If the present-day sea level is maintained over the next 1 000 years, the Pearl River delta is expected to continue to migrate southwards and should merge with Lantau Island. However, the design life of the airport is 100–150 years. Additional impacts not considered here are the road and rail links between the airport and the urban areas of Hong Kong.

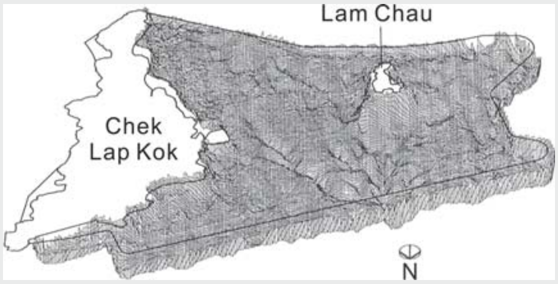


Fig. TB2.10.2. A three-dimensional model of the ground surface after dredging within the area of the airport platform (from Plant et al. 1998)

Fig. TB2.10.3. View of the Hong Kong International Airport construction site during 1995 (© K. Bartlett, Pacific Century Publishers Limited)

Fig. TB2.10.4. A trailing suction hopper dredger from the Netherlands similar to the type used for the reclamation of the new Hong Kong International Airport in action in Hong Kong. Sand is placed hydraulically using a technique known as rainbowing (© W. W.-S. Yim) as trace metals and nutrients with a resultant change in the concentrations of the dissolved and particulate fractions, particularly in regions of low salinity; (*b*) they provide a particle surface which may serve as a site for bacterial attachment, at least when the particles occur in flocs; and (*c*) the particles and their absorbed materials form sources of nutrients and trace metals for suspension-feeding organisms. Taken together these characteristics infer effects that might result from decreasing the amount of sediment discharged from a dammed river. On the positive side of the equation, decreased sediment loads point to decreased turbidity levels necessary for healthy primary production. However, as a result of decreased suspended sediment delivered offshore of the Mississippi River in addition to increased nutrient loads, the water clarity has decreased due to the increase in chlorophyll biomass (Rabalais et al. 2002). On the negative side of the equation, reduced loads of sediment, nutrients and trace metals discharged from a river will greatly influence the trophic structure of any ecosystem. One secondary effect of changing the material flux of a river would be to change the diversity and structure of the benthic coastal ecosystem, from one of bacterial preference and sediment tolerance, to one with plankton preference and sediment intolerance (Farrow et al. 1983).

2.6.3 The Vitality of Coastal Wetlands, Mangroves and Reefs

Many coastal ecosystems depend on the seasonal variability of water levels, water salinity and water clarity. A reduced seasonal flood-wave limits the flooded area of a delta and the health of the wetland community. Examples abound, from breeding habitats of birds and coastal mammals to the algal and seagrass communities of coastal areas. River diversion is the most extreme example of an anthropogenic influence on the coastal zone. In Canada, diversion schemes include the wholesale diversion of rivers, with massive effects on the coastal zone (D'Anglejan 1994). In the residual rivers, lower water levels are predicted to increase the susceptibility of riverbanks cut into sensitive clays, leading to mass wasting and increased estuarine sedimentation. Higher rates of sedimentation in the estuary, coupled with increased intertidal vegetation, further alter the estuarine circulation with augmented salt intrusion and increased particle retention. Brackish swamps will invade with time.

Estuaries marked with increased and regulated flows are expected to rapidly prograde their offshore delta, reduce any winter ice cover and modify their shoreline profile over time. The increased size of the plume would disperse fine-grained sediment over a larger area and probably change the offshore benthic ecosystem. Together, these conditions are expected to lead to changes in offshore circulation patterns.

Increased siltation in some areas can stimulate the growth of mangroves just as decreased coastal siltation can decrease the growth of mangroves (Wang et al. 1998). Increased siltation in the coastal zone could hinder the growth of offshore coral reefs.

In tropical systems, the major polluter is considered to be river-borne mud. Most tropical estuaries are now extremely shallow and turbid due to a combination of intense tropical rainfall and the lack of effective restrictions on human activities in the river catchment that lead to increased erosion. Dams and water diversion schemes in tropical catchments (e.g., Mekong) are predicted to result in:

- increased salinity intrusion up the estuary;
- increased wave-induced coastal erosion reflecting a decrease (expected) in coastal sedimentation (during the high flow season), that would otherwise provide protection for the coast;
- reduced annual flood wave, which would increase the likelihood of estuarine siltation; and
- decreased wet-season flushing of acid sulfates formed in the dry season in the top layer of the soils in the upper delta (acid sulfate being a significant hindrance to farming in the dry season).

2.6.4 Sediment Dispersion and Grain Size Effects

Hinterland changes in a river's hydrography will have profound changes on the hydrodynamics that control the energy level within a delta system and the flux of a material load across a delta system. This truism leads to new understandings of how anthropogenic changes on a river system fundamentally change the residence time of sediment within a delta. Changes will lead to differences in the residence time proportioned to different sediment grain sizes. As the sediment load within a river system is artificially reduced, concomitant with reduction of the flood wave and river-bank control (for example, the Ebro River, Spain; Sanchez-Arcilla et al. 1998), wave energy begins to reshape the delta deposits. This reshaping increases coastal erosion in certain areas while longshore transport increases the deposition rate in other areas. As a consequence, clayey material has a decreased residence time on the delta flood plain, whereas sand material has an increased residence time along the exposed coast.

The dispersion of river-borne particulate load away from the river mouth depends on coastal circulation (i.e., upwelling, downwelling, longshore currents), and on the character of the emanating plume (i.e., surface or subsurface). Road construction and newly introduced river-valley farming along Taiwanese rivers, for example, have led to highly elevated sediment loads and an increased likelihood of subsurface (hyperpycnal) flows (Syvitski 2003b). These hyperpycnal plumes flow along the seafloor and travel directly down the continental slope, often within submarine canyons. Such currents will reduce the flux of sediment to the shelf environment and reduce the availability of freshwater and nutrients to the coastal zone ecosystems. In contrast, reservoir control will reduce the flood wave and the concomitant delivery of sediment to the coastal zone. In affected coastal environments the dispersal of sedimentary material is greatly reduced (Syvitski et al. 1998).

2.7 Summary

2.7.1 Impacts of Local, Regional and Global Sea-level Fluctuations

Scientific estimates of sea-level rise associated with global change have often dominated the political debate on climate change impacts in the coastal zone. Over the last decade there has been an increase in the accuracy of global sea-level measurement from techniques such as satellite altimetry and geodetic levelling together with the refined global viscoelastic analysis of glacio-isostatic adjustment. However, there is still a need for detailed research at local and regional scales into sea-level change and more accurate prediction of the impact of these changes.

Placing present and predicted sea-level changes within a geological context is important, so as to provide a perspective on the cyclical nature of sea-level and the extent to which current and predicted sea-level changes are perturbations beyond natural cycles, particularly the 100 000-year glacial/interglacial cycles. The geological record also shows that there has been a globally variable but predictable coastal response to the sea-level rise that followed the last glacial maximum. In addition, recent geological research shows prospects for linking recent geological records (the last 2 000 years) with sea surface temperature measurements and regional climate change.

The historical record of sea-level change interpreted from tide-gauge data demonstrates that the average rate of sea-level rise was less in the 19th century than in the 20th century. However, the raw tide-gauge data need to be corrected for local and regional influences either with modelling calculations or directly by geological investigations near tide-gauge sites. Resultant mean sea-level trends for the 20th century show a mean sea-level rise in the range of 1–2 mm yr^{-1} with a central value of 1.5 mm yr^{-1}. There remains some debate about these results, which in part relates to the different correction methods.

An important element of sea-level change research is the prediction of impacts on coastal dynamics. This is underpinned by intensive studies, such as LOIS, the UK program that detailed the evolving coastal dynamics following the postglacial sea-level rise for a section of the UK coast. Examination of the impacts of a rising sea level on different types of coast (sandy coasts, deltaic coasts, tropical coasts, low-latitude coasts) demonstrated that many are already eroding and that new threats are appearing in areas such as the Arctic, where changes in the extent of sea ice have in places produced a different wave climate with consequent coastal impacts.

The most recent scientific projections of a sea-level rise are within the range of 0.09 to 0.88 m for the period 1990 to 2100 with a central value of 0.48 m and, if current rates of terrestrial storage continue, the projections could vary by as much as −0.21 to +0.11 m. Even the achievement of the central value by 2100 would require a rate of sea-level rise between 2.2 and 4.4 times the rate for the 20th century.

In response to these predictions, various coastal vulnerability assessments have been undertaken. Initially a common global methodology was developed by the IPCC but this proved either too difficult or inappropriate for a number of countries. Regional vulnerability assessments have been conducted for specific areas such as the Pacific, where there are many low-lying developing countries perceived to be at risk. Alternative approaches to the IPCC common methodology include attempts to refine and upscale regional vulnerability data (as in the SURVAS project) or to develop specific coastal vulnerability indices (as used in the United States of America).

Although the management response to sea-level rise varies around the world, generally, it comprises some combination of the three options of retreat, accommodate or protect. A distinction needs to be made between natural coastal vulnerability and the vulnerability of human lives and property that may be put at risk by the effects of climate change and sea-level rise. In many cases, poor coastal planning has resulted in the need for rapid and expensive adjustment to the consequences of sea-level change. However, there is a clear need for better understanding of local sea-level change in addition to adopting a precautionary approach in planning to meet the consequences of predicted global sea-level rise.

2.7.2 Sediment Flux to the Coast

River systems evolve across time, influenced by paleo-conditions within the watershed, shorter period fluctuations in climate and, most recently, perturbations by humans. The sediment load delivered by world rivers is a determining factor for the long-term stability of our coastal zones. Ocean energy (tides, waves, currents) reworks the river-supplied coastal sediment to form and maintain our varied coastlines: estuaries, beaches and deltas. If the sediment supply from the land is reduced, then ocean energy will begin to relentlessly attack and erode shores.

Apart from humans, climate shifts are often the major driving factor on sediment flux. Large continents are

Text Box 2.11. Mar del Plata: A cautionary tale

Gerardo M. E. Perillo

Mar del Plata is the most important tourist city of Argentina. It has about 500 000 permanent inhabitants but, during the summer period (December-February), the population may increase 6-fold. Founded in 1874, the extended bay beaches between points of Devonian orthoquartzitic rocks were the main features that attracted visitors. At both sides of the city, Pleistocene loess cliffs (up to 25 m high) are a significant source of sediment for littoral transport.

The coast at Mar del Plata has a general trend SW-NE (Fig. TB2.11.1) and the coastline receives waves from the south and southeast for about 80% of the time, resulting in net northward littoral transport of about 390 000 m^3yr^{-1} (Caviglia et al. 1991). The coast is microtidal, having a semidiurnal tide with mean spring and neap ranges of 0.91 and 0.61 m, and wave height is between 0.5 to 5.5 m with periods between 6 and 16 s (Sunrise Technical Consultants 1968).

Mar del Plata was also a fishing village. As the population grew and agricultural development on the adjacent Pampas increased, the Mar del Plata harbour was constructed between 1914 and 1919 by partly closing a small bay with two large jetties. Construction proceeded in the absence of oceanographic evaluation.

Shortly after harbour construction, considerable erosion occurred on most beaches north of the harbor and a dissipative beach started to build to the south (Punta Mogotes Beach). Sand retention on the beaches became a priority for local and provincial authorities, with construction of a series of wooden groynes in the 1930s, replaced by cement in the 1950s. As more sand was retained by the urban beaches, erosion extended to other beaches, requiring more groyne construction.

As beach erosion grew more extensive north of the city, the associated Pleistocene loess cliffs were exposed to wave attack and started to retreat. By the 1960s, cliff erosion endangered houses, highway infrastructure and beach tourism, and in 1972–74 a 5 m high wall was constructed along 800 m of the coast in addition to new groynes.

By this time, marked erosion processes had reached the next town (Santa Clara del Mar) located 20 km to the north; between both towns beaches had disappeared and the cliffs were fully exposed and actively retreating. Nevertheless, groynes were still being built along Santa Clara del Mar, which by 1977 had lost practically all its beaches.

Between 1978 and 1984, a completely new plan for building groynes and breakwaters was developed, and groynes (Fig. TB2.11.2) were built from Mar del Plata to the mouth of Mar Chiquita coastal lagoon (about 40 km to the north); the coast of this area was retreating at an average rate of 5 $m\,yr^{-1}$ (Schanck et al. 1990). Cliffs were then protected by placing riprap stone along their base (Fig. TB2.11.2c).

Some of the semi-enclosed groynes and breakwaters built were very closely spaced, so that small artificial bays developed (Fig. TB2.11.2a) with a very restricted circulation. As sand filled these bays, the beach profile became very steep (> 30°) with water depths of 3–4 m attained in a few meters. These were not only dangerous for swimming, but the resulting embayments in northern locations became polluted by Mar del Plata sewage discharged from offshore (5 km) outflows.

In 1998, Mar del Plata city and harbour authorities accepted that groynes and breakwaters were not a solution. Major dredging of the harbour mouth produced coarse to very coarse sand that was pumped to Grande, Varese and Bristol beaches (Fig. TB2.11.2). The Grande and Bristol beaches were then about 250 m wide and elevated by 1.5 m above the previous beach level. All the groynes at Bristol beach were fully covered by the sand.

A few months after the nourishment, a major storm produced flooding in the city and river flows from the hills that severely eroded the beaches and moved sand offshore. Wave action has now eroded 50% of the original nourishment material leaving beaches 170–190 m wide, and all groynes have outcropped and are now active in trapping sediment.

Although the solution of nourishing the beaches from the harbour mouth shoal sand may have been a good solution, it was made without a clear understanding of sand grain-sizes required to produce an equilibrium beach. Neither was the solution a "one-time" nourishment operation. The probable "best solution" to preserve beaches to the north of the harbour is to dredge or pump sand that accumulates along the South Jetty and at Mogotes Beach and bypass it to the side of the North Jetty, thus allowing the local dynamics to return the littoral transport lost some 90 years ago.

influenced by a variety of climatic phenomena over different time periods. Individual regions may respond differently to climatic forcing, resulting in variable changes in sediment flux for a given climatic event. The response will depend on the duration of the climate fluctuation and the variability in spatial properties of such parameters as relief, geology and hydrological processes.

The modern global flux of sediment to the coastal zone (20 Gt yr^{-1}) has two competing Anthropocene forces:

a land-use practices that increase soil erosion (agriculture, deforestation, industrialisation, mining), and
b practices that decrease soil erosion (engineering of waterways including the trapping of sediment by reservoirs).

While humans have substantively increased the continental flux of sediment during the last two millennia, most of the land-derived erosional sediment remains stored someplace between the uplands and the sea. Storage of sediment in large reservoirs constructed during the last 50 years has decreased the global flux of sediment to the coastal zone by 30%. By decreasing sediment loads, coastal erosion is accelerated and coastal ecosystems deteriorate. There is now good documentation on the reduction of local fisheries (e.g., sardine and shrimp catch) as a consequence of hinterland reservoir construction. The coupling of increased nutrient inputs and decreased sediment loads may promote coastal-zone eutrophication and hypoxia.

Future research must identify population thresholds and behaviours that have strong hydrological and sediment flux consequences and lag-times in coastal response. The influence of humans and/or climate affects smaller river basins more dramatically than larger river basins, due to the modulating ability of large rivers. New techniques must be developed to address the coastal response to these sensitive smaller systems. Scaling techniques must also be employed to address the quality of our global databases as: (*a*) most of the observational data was determined across only a few years and interannual variability can exceed mean values by an order of

◀

Fig. TB2.11.1. Schematic map of the harbour and adjacent beach areas of Mar del Plata, Argentina

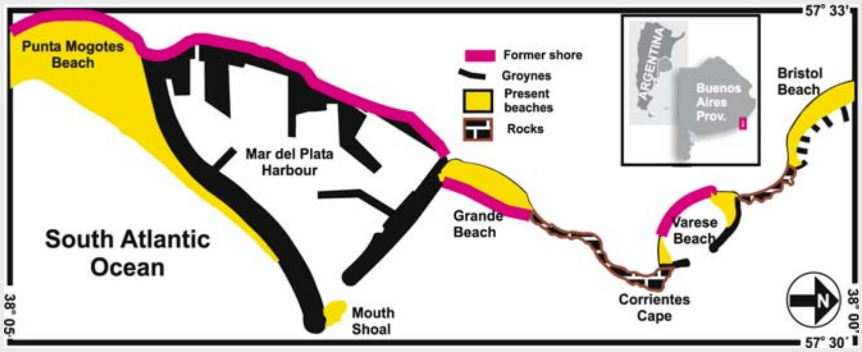


Fig. TB2.11.2. Some of the mechanisms of beach and cliff protection constructed along the Mar del Plata coast, Argentina

magnitude, and (*b*) observational datasets are already a few decades old during a time of rapid change resulting from increased human impacts.

2.7.3 Dynamics at the Estuarine Interface

A major portion of the sedimentary material reaching the coast may be retained in estuaries and deltas, but for most coastal systems the sediment retention level is largely unknown. Geomorphology is probably the most important single factor controlling sediment retention, as the degree of tidal-wave asymmetry is strongly related to the geomorphological influence on tidal propagation. Interactions between geomorphology and advection processes are highly non-linear, making the fate of sediment input into coastal areas difficult to predict, across both short and long time periods.

Even though smaller rivers have relatively large sediment loads, they do not have the strength to drive sediment through the estuary, especially on meso- and macro-tidal coasts where most of the material is retained within the estuary. In the absence of river floods that can overwhelm the system and flush freshwater all the way to the mouth of the estuary, the filtering, trapping and processing of suspended particles in the estuary will be a function of internal circulation and the form and dynamics of the turbidity maximum. Many such estuaries require continuous dredging to maintain navigability. Exceptional rainfall from hurricanes or ENSO events, or the impact of earthquakes, may modify the dynamic equilibrium toward which all estuaries approach. Over timescales of years, the natural system may be at quasi-equilibrium in the sense that the size, shape and depth of the system may change only very slowly, evolving at timescales of decades. This is important because in relatively un-impacted settings, humans have time to adapt to changing estuaries and coasts. However, anthropogenic influences on estuaries are now increasingly influencing circulation processes and changing estuarine geomorphology and thereby modifying the trapping mechanisms. Artificial structures such as harbours, jetties and breakwaters have little or no capability to adapt to the constant changes in estuarine dynamics.

In the wet tropics, intense rainfall coupled with deforestation, land clearing, overgrazing and other poor farming practices increase soil erosion and sediment flux many times above natural backgrounds. Siltation results in decreased water visibility and increased muddiness, often causing environmental degradation by the smothering of benthic organisms, driving changes in the biological properties of the water column and benthic food chains (especially in tropical river deltas), and leading to economic losses for the tourism industry due to poor aesthetics. When sediment from human-induced soil erosion exceeds the trapping capacity of the estuary (a process exacerbated by estuarine wetlands reclamation and other human activities), the mud is deposited in coastal waters. This change in estuarine and coastal properties may be very rapid, occurring within a few decades, and may threaten the life of many coral reefs. For tropical estuaries and the coastal seas, environmental degradation by mud is a serious problem.

This situation contrasts with that in developed countries in middle latitudes, where estuaries are generally suffering from sediment starvation due to extensive damming and river flow regulation. Sediment retention by dams leads to accelerated coastal recession (e.g., the deltas of the Colorado, Nile, Ebro, Mississippi and Volta rivers). Water diversion schemes also accelerate coastal erosion.

2.7.4 Groundwater Inputs

Both terrestrial and marine forces drive underground fluid flows in the coastal zone. Hydraulic gradients on land result in groundwater seepage near shore and may contribute to flows further out on the shelf from confined aquifers. Marine processes such as tidal pumping and current-induced topographic flow may occur anywhere on the shelf where permeable sediments are present. The terrestrial and oceanic forces overlap spatially and thus measured fluid flow through coastal sediments may be a result of composite forcing. We thus define "submarine groundwater discharge" (SGD) as any flow out across the seabed, regardless of composition or driving force.

Submarine porewater exchange (SPE) is characterised by low specific flow rates that make detection and quantification difficult. However, because such flows (both recharge and discharge) may occur over large areas, the total flux is significant. Discharging fluids, whether derived from land or composed of re-circulated seawater, will react with sediment components changing its composition. These fluids may thus become a source of biogeochemically important constituents including nutrients, metals and radionuclides. If derived from land, such fluids will represent a pathway for new material fluxes to the coastal zone and may result in diffuse pollution in areas where contaminated groundwater occurs.

Additional data collection is required in many areas, especially in South America, Africa and southern Asia where, to our knowledge, no or few assessments are currently described in the literature. We recommend an approach that targets representative types of coastal aquifers based on geology (e.g., karst, coastal plains, deltaic) and environmental parameters (e.g., precipitation, temperature). The production of an SGD database and globalisation efforts are necessary to integrate SGD on a global scale.

Improvements must also be made to techniques used for measurements of SGD. The sensitivity of porewater exchange to local pressure perturbations necessitates the development of new non-invasive methods, and we need to revise our monitoring, measuring and sampling strategies in permeable seabeds. The calculation of realistic estimates of advective porewater exchange in the coastal zone and on the shelf requires concurrent data on bottom current characteristics, sediment topography and sediment permeability. Long-term studies, isotopic signatures and certain chemical and physical properties of the pore fluids may provide indications of the origin and physical forcings of the pore-fluid flows. However, in many cases, several of these processes will be active simultaneously and their separation based on measured data may be very difficult if not impossible. An indispensable tool for overcoming this problem is the modelling of the various transport processes and their effects on the biogeochemical cycles. A new generation of dynamic models is needed to explain the porewater flow observed in natural environments.

The implication of SGD for coastal area management requires assessment of the importance of hydrologic flow in a particular region in a much more time-efficient manner than currently exists. This may require expanding our use of remote sensing, geophysical tools and typology.

2.7.5 The Human Dynamic

Changes to the natural environment due to human intervention impact the flux and flow of water, sediments and nutrients on local, regional and global scales. Construction of dams, deforestation, urbanisation and use of groundwater have modified river runoff, sedimentation patterns, coastline structure and relative sea level. Changes to timing of nutrient fluxes and sediment load have affected trophic structures within ecosystems. River diversion and modified seasonal variability of water levels have affected the health of coastal wetlands, mangrove and coral reef communities as well as leading to changes in shoreline profile and ecosystem composition of rivers, estuaries and coastal seas. Awareness of anthropogenic impacts needs to lead to technological innovations to manage the system as it exists, and to minimise further degradation of coastal systems (see Text Box 2.11).

References

Aagaard K, Darby DA, Falkner K, Flato G, Grebemeier J, Measures C, Walsh JE (1999) Marine science in the Arctic: a strategy. Arctic Research Consortium of the United States (ARCUS), Fairbanks, AK

Aksornkoae S (1993) Ecology and Management of Mangroves. IUCN, Bangkok, Thailand

Alam M (1996) Subsidence of Ganges-Brahmaputra Delta of Bangladesh and associated drainage, sedimentation and salinity problems. In Milliman JD and Haq BU (eds) Sea-level rise and coastal subsidence: causes, consequences and strategies. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 169–192

Alverson K, Oldfield F, Bradley RS (eds) (2001) Past global changes and their significance for the future. IGBP Science Series No. 3: Environmental variability and climate change (PAGES), Pergamon

Anisimov OA, Nelson FE (1996) Permafrost distribution in the northern hemisphere under scenarios of climatic change. Global and Planetary Change 14:59–72

Anon (1996) Geotechnical aspects of Hong Kong's New Airport. Ground Engineering Special Supplement December 1996

Arbogast AF (2000) Estimating the time since final stabilization of a perched dune field along Lake Superior. Professional Geographer 52(4):594–606

Are FE (1999) The role of coastal retreat for sedimentation in the Laptev Sea. In: Kassen H, Bauch HA, Dmitrenko IA, Eichen H, Hubberten H-W, Melles M Thiede J, Timokhov LA (eds) Land-Ocean Systems in the Siberian Arctic: Dynamics and History, Springer, Berlin, pp 287–295

Arthurton RS (2003) The fringing reef coasts of eastern Africa – present processes in their long-term context. Western Indian Ocean Journal of Marine Science 2(1):1–13

Back W, Hanshaw BB, Pyler TE, Plummer LN, Weide AE (1979) Geochemical significance of groundwater discharge in Caleta Xel Ha, Quintana Roo, Mexico. Water Resources Research 15: 1521–1535

Baker RGV, Haworth RJ (2000) Smooth or oscillating late Holocene sea-level curve? Evidence from cross-regional statistical regressions of fixed biological indicators. Marine Geology 163(1–4): 353–365

Bard E, Hamelin B, Fairbanks RG (1990) U/Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130 000 years. Nature 346:456

Bates RL, Jackson JA (1984) Dictionary of Geological Terms. American Geological Institute, NY

Beets, DJ, Roep TB, Westenrhoff WE (1996) The Holocene Bergen Inlet: closing history and related barrier progradation. In: Beets DJ, Fischer MM, Gans W de (editors) Coastal Studies on the Holocene of the Netherlands. Boom-Planeta, The Netherlands, pp 97–131

Bell RG, Hume TM, Hicks DM (2001) Planning for climate change effects on coastal margins. A report prepared for the Ministry for the Environment as part of the New Zealand Climate Change Programme, Ministry for the Environment, Wellington, New Zealand

Belperio AP (1995) Quaternary. In: Drexel JF, Preiss WV (eds) The geology of South Australia, vol 2: the Phanerozoic. South Australia Geological Survey Bulletin 54:219–281

Bender ML, Fairbanks RG, Taylor FW, Matthews RK, Goddard JG, Broecker WS (1979) Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies. Geological Society of America Bulletin, part I, vol 90, pp 577–594

Berner EK, Berner RA (1987) The global water cycle: geochemistry and environment. Prentice-Hall, Englewood Cliffs, NJ

Bird ECF (1993) Submerging coasts: the effects of a rising sea level on coastal environments. John Wiley and Sons, Chichester

Bird ECF (1996) Coastal erosion and rising sea level. In Milliman JD, Haq BU (eds) (1996) Sea-level rise and coastal subsidence: causes, consequences and strategies. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 87–103

Bird ECF (2000) Coastal geomorphology: an introduction. Wiley, Chichester

Blanchon P, Eisenhauer A (2001) Multi-stage reef development on Barbados during the last interglaciation. Quaternary Science Reviews 20:1093–1112

Bokuniewicz HJ, Pavlik B (1990) Groundwater seepage along a barrier island. Biogeochemistry 10:257–276

Boudreau BP, Huettel M, Froster S, Jahnke RA, McLachlan A, Middelburg JJ, Nielsen P, Sansone F, Taghon G, Van Raaphorst W, Webster I, Weslawski JM, Wiberg P, Sundby B (2001) Permeable marine sediments: overturning an old paradigm. EOS 82: 133–136

Bray MJ, Hooke JM (1997) Prediction of soft-cliff retreat with accelerating sea level rise. Journal of Coastal Research 13(2): 453–467

Bressolier C, Froidefond J-M, Thomas Y-F (1990) Chronology of coastal dunes in the south-west of France. In: Bakker Th W, Jungerius PD, Klijn JA (eds) Dunes of the European coasts. Geomorphology – hydrology – soils. Catena Supplement 18: 101–107

Broecker WS (1979) Thermohaline circulation, the Achilles heel of our climate system: will man-made CO_2 upset the current balance? Science 278:1582–1588

Brown BE, Dunne RP, Goodson MS, Douglas AE (2000) Bleaching patterns in reef corals. Nature 404:99–105

Bruun P (1962) Sea-level rise as a cause of shore erosion. Journal of Waterways and Harbors Division (ASCE) 88:116–130

Buddemeier RW, Smith SV (1988) Coral reef research in an era of rapidly rising sea level: predictions and suggestions for long-term research. Coral Reefs 7:51–56

Bugna GC, Chanton JP, Cable JE, Burnett WC, Cable PH (1996) The importance of groundwater discharge to the methane budgets of nearshore and continental shelf waters of the northeastern Gulf of Mexico. Geochimica Cosmochimica Acta 60:4735–4746

Burnett WC, Turner J (2001) LOICZ group investigates groundwater discharge in Australia. LOICZ Newsletter 18:1–4

Burnett WC, Taniguchi M, Oberdorfer J (2001) Measurement and significance of the direct discharge of groundwater into the coastal zone. Journal of Sea Research 46(2):109–116

Burnett WC, Chanton J, Christoff J, Kontar E, Krupa S, Lambert M, Moore W, O'Rourke D, Paulsen R, Smith C, Smith L, Taniguchi M (2002) Assessing methodologies for measuring groundwater discharge to the ocean. EOS 83:117–123

Burnett WC, Chanton JP, Kontar E (2003) Submarine groundwater discharge. Biogeochemistry 66:1–202

Burt RA (1993) Groundwater chemical evolution and diagenetic processes in the Upper Floridan aquifer, southern South Carolina and northeastern Georgia. US Geological Survey Water-Supply Paper 2392

Cable JE, Burnett WC, Chanton JP, Corbett DR, Cable PH (1997) Field evaluation of seepage meters in the coastal marine environment. Estuarine, Coastal and Shelf Science 45:367–375
Cai WJ, Wang Y (1998) The chemistry, fluxes and sources of carbon dioxide in the estuarine waters of the Satilla and Altamaha rivers, Georgia. Limnology and Oceanography 43:657–668
Cathles LM (1990) Scales and effects of fluid flow in the upper crust. Science 248:323–330
Caviglia FJ, Pousa JL, Lanfredi NW (1991) A determination of the energy flux constant from dredge records. Journal of Coastal Research 7:543–550
Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000) Arctic and boreal ecosystems of western North America as components of the climate system. Global Change Biology 6:211–223
Chappell, J (1993) Contrasting Holocene sedimentary geologies of the lower Daly River, northern Australia and lower Sepik-Ramu, Papua New Guinea. Sedimentary Geology 83:339–358.
Chappell, J, Omura A, Esat T, McCulloch M, Pandolfi J, Ota Y, Pillans B (1996) Reconciliation of Late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth and Planetary Science Letters 141:227–236
Christiansen C, Bowman D (1986) Sea-level changes, coastal dune building and sand drift, NW Jutland, Denmark. Geografisk Tidsskrift 86:28–31
Christiansen C, Dalsgaard K, Moller JT, Bowman D (1990) Coastal dunes in Denmark. Chronology in relation to sea level. In: Bakker Th W, Jungerius PD, Klijn JA (eds) Dunes of the European coasts. Geomorphology – hydrology – soils. Catena Supplement 18:61–70
Conley DC, Inman DL (1994) Ventilated oscillatory boundary layers. Journal of Fluid Mechanics 273:261–284
Considine DM (ed) (1995) Van Nostrand's scientific encyclopedia, 8th edn. NY, Van Nostrand, Reinhold
Cooper HH, Kohout FA, Henry HR, Glover RE (1964) Sea water in coastal aquifers. US Geological Survey Water Supply Paper 1613-C:84
Cowell PJ, Thom BG (1994) Morphodynamics of coastal evolution. In: Carter RWG, Woodroffe CD (eds) Coastal evolution: late Quaternary shoreline morphodynamics. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 33–86
Crossland CJ (1982) Dissolved nutrients in reef waters of Sesoko Island, Okinawa: a preliminary study. Galaxea 1:47–54
Curtis WF, Culbertson K, Chase EB (1973) Fluvial-sediment discharge to the oceans from the conterminous United States. US Geological Survey Circular 670:1–17
D'Anglejan B (1994) Potential sedimentological impacts of hydroelectric developments in James Bay and Hudson Bay. James Bay Publication Series, Paper No. 5
Danilov ID (2000) Submarine permafrost of the Arctic Shelf and related processes of cryogenic lithomorphogenesis. Oceanology 40:714–722
Davidson-Arnott RGD, Pyskir NM (1988) Morphology and formation of a Holocene coastal dune field, Bruce Peninsula, Ontario. Geographie Physique et Quaternaire 42(2):163–170
Davis JL, Mitrovica JX (1996) Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America. Nature 379:331–333
Day JW, Martin JF, Cordoch L, Templet PH (1997) System functioning as a basis for sustainable management of deltaic ecosystems. Coastal Management 25:115–153
Dedkov AP, Mozzherin VI (1992) Erosion and sediment yield in mountain regions of the world. In: Walling DE, Davies TR, Hasholt B (eds) Erosion, debris flows and environment in mountain regions (Proceedings of the Chengdu Symposium, July 1992). IAHS Publication 209:29–36
D'Elia CF, Webb KL, Porter JW (1981) Nitrate-rich groundwater inputs to Discovery Bay, Jamaica: a significant source of N to local reefs? Bulletin of Marine Science 31:903–910
de Vries I (2001) Shoreline and land-use development perspectives in the context of long-term decreasing functional diversity in the Delta Region, SW Netherlands. In: von Bodungen B and Turner RK (eds) Science and Integrated Coastal Management, Dahlem Workshop Report 85, Dahlem University Press, Berlin, pp 113–120
Dionne JC (1963) Towards a more adequate definition of the St Lawrence estuary. Journal of Geomorphology 7:36–44
Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J (1994) Carbon pools and flux of global forest ecosystems. Science 263:185–190
Doornkamp JC (1998) Coastal flooding, global warming and environmental management. Journal of Environmental Management 52:327–333
Douglas BC (1991) Global sea level rise. Journal of Geophysical Research 96(C4):6981–6992
Douglas BC (1997) Global sea rise: a redetermination. Surveys in Geophysics 18:279–292
Douglas BC (2001) Sea level change in the era of the recording tide gauge. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea-level rise: history and consequences. Academic Press, International Geophysics Series vol 75, pp 37–64
Douglas, BC, Peltier, WR (2002) The puzzle of global sea-level rise. Physics Today, March 2002, pp 35–40
Douglas I (1993) Sediment transfer and siltation. In: Turner BL, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB (eds) The earth as transformed by human action. Cambridge University Press, Cambridge, pp 215–234
Dronkers J, van Leussen W (1988) Physical processes in estuaries. Springer-Verlag, Berlin
Dunbar R, Cole J (1999) Annual records of tropical systems (ARTS). Recommendations for research. PAGES Workshop Report, Series 99-1
Eicken H (2004) The role of Arctic sea ice in transporting and cycling terrestrial organic matter. In: Stein R, Macdonald RW (eds) The organic carbon cycle in the Arctic Ocean: present and past. Springer-Verlag, Berlin
Ellison JC, Stoddart DR (1991) Mangrove ecosystem collapse with predicted sea-level rise: Holocene analogues and implications. Journal of Coastal Research 7:151–165
El-Sayed M Kh (1996) Rising sea level and subsidence of the northern Nile Delta. In: Milliman JD, Haq BU Sea-level Rise and Coastal Subsidence. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp 215–233
Emery KO (1968) Relict sediments on continental shelves of the world. American Association of Petroleum Geologists 52:445–464
Emery KO, Uchupi E (1972) Western North Atlantic Ocean: topography, rocks, structures, water, life and sediments. American Association of Petroleum Geologists Memoir 17
Emiliani C (1955) Pleistocene temperatures. Journal of Geology 63: 539–578
ERL (Asia) Limited (1982) Proposed replacement airport at Chek Lap Kok – potential impact on the marine environment. Prepared for the Civil Aviation Department, Hong Kong Government, Hong Kong
Farrow GE, Syvitski JPM, Tunnicliffe V (1983) Suspended particulate loading on the macrobenthos in a highly turbid fjord: Knight Inlet, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 40:100–116
Forbes DL, Taylor RB (1994) Ice in the shore zone and the geomorphology of cold coasts. Progress in Physical Geography 18:59–89
Forbes DL, Orford JD, Carter RWG, Shaw J, Jennings SC (1995) Morphodynamic evolution, self-organization and instability of coarse-clastic barriers on paraglacial coasts. Marine Geology 126:63–85
Forbes DL, Orford JD, Taylor RB, Shaw J (1997) Interdecadal variation in shoreline recession on the Atlantic Coast of Nova Scotia. In: Proceedings of the Canadian Coastal Conference '97, Guelph, Ontario, Canadian Coastal Science and Engineering Association, Ottowa, Canada, pp 360–374
Freeman C, Evans CD, Monteith DT (2001) Export of organic carbon from peat soils. Nature 412:785
Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall Inc. Englewood Cliffs, NJ
Froidefond J-M, Legigan P (1985) La grande dune du Pilat et la progression des dunes sur la littoral Aquitaine. Bulletin Institut Geologique du Bassin d'Aquitaine 38:69–79
Fryberger S, Krystinik LF, Schenk CJ (1990) Tidally flooded back-barrier dunefield, Guerrero Negro area, Baja California, Mexico. Sedimentology 37: 1–23

Gallup CD, Edwards RL, Johnson RG (1994) The timing of high sea levels over the past 200 000 years. Science 263:796–800
Garrels RM, MacKenzie FT (1971) Evolution of sedimentary rocks. Norton & Co, New York
Gehlen M, Malschaert H, van Raaphorst WR (1995) Spatial and temporal variability of benthic silica fluxes in the southeastern North Sea. Continental Shelf Research 15:1675–1696
Giles PT, McCann SB (1997) Foredune development on Iles de la Madeleine (Quebec), Atlantic Canada. Canadian Journal of Earth Sciences 34:1467–1476
Goodwin I (2002) Unravelling climate influences on late Holocene sea-level variability. In: Anson M, Battarbee R, Birks J, Oldfield F (eds) Global change in the Holocene. Edward Arnold, pp 406–421
Goodwin I, Harvey N, van der Plassche O, Oldfield F and Oglesby R (2000) Prospects of resolving climate-induced sea-level fluctuations over the last 2 000 years. Transactions of the American Geophysical Union (EOS) 81(28):311–314
Gordon DC Jr, Boudreau PR, Mann KH, Ong JE, Silvert WL, Smith SV, Wattayakorn G, Wulff F, Yanagi T (1996) LOICZ biogeochemical modelling guidelines. LOICZ Reports & Studies No. 5, LOICZ, Texel, The Netherlands
Gornitz V (1995) A comparison of differences between recent and late Holocene sea level trends from eastern North America and other selected regions. In: Finkl CW Jr (ed) Holocene cycles: climate, sea levels and sedimentation. Journal of Coastal Research, Special Issue No. 17:287–297
Gornitz V (2001) Impoundment, groundwater mining, and other hydrologic transformations: impacts on global sea level rise. In: Douglas BC, Kearney M.S, Leatherman SP (eds) Sea level rise: history and consequences. Academic Press, San Diego, CA, pp 97–119
Gornitz V, Lebedeff S (1987) Global sea level changes during the past century. In: Nummedal D, Pilkey OH, Howard JD (eds) Sea level fluctuation and coastal evolution. Society for Economic Paleontologists and Mineralogists Special Publication 41:3–16
Gornitz V, White TW (1992) A coastal hazards database for the US east coast. ORNL/CDIAC-45, NDP-043A. Oak Ridge National Laboratory, Oak Ridge, TN
Gornitz V, Daniels RC, White TW, Birdwell KR (1994) The development of a coastal risk assessment database: vulnerability to sea level rise in the US southeast. Journal of Coastal Research, Special Issue No. 12:327–338
Gornitz V, Couch S, Hartig EK (2002) Impacts of sea level rise in the New York metropolitan area. Global and Planetary Change 32: 61–88
Gorsink JP, Baker GC (1990) Salt fingering in subsea permafrost: some stability and energy considerations. Journal of Geophysical Research 95:9575–9584
Guan WB, Wolanski E, Dong LX (1998) Cohesive sediment transport in the Jiaojiang River estuary, China. Estuarine, Coastal and Shelf Science 46:861–871
Guay CK, Klinkhammer GP, Falkner KK, Benner R, Coble PG, Whitledge TE, Black B, Bussell FJ, Wagner TA (1999) High-resolution measurements of dissolved organic carbon in the Arctic Ocean by in situ fiber-optic spectrometry. Geophysical Research Letters 26:1007–1010
Guillen J, Palanques A (1997) A historical perspective of the morphological evolutions in the lower Ebro River. Environmental Geology 30:174–180
Haida S (2000) Transport de matières et bilan de l'érosion mécanique et de l'altération chimique dans un bassin versant de la zone semi-aride: Impact des variations climatiques et des activités humaines. Thèse Doctorat d'Etat, Universite Ibn Tofail, Kénitra
Hammar-Klose E, Thieler ER (2001) Coastal vulnerability to sea-level rise: a preliminary database for the US Atlantic, Pacific and Gulf of Mexico coasts. US Geological Survey Digital Data Series DDS-68
Harrison WD, Musgrave D, Reeburgh WS (1983) A wave-induced transport process in marine sediments. Journal of Geophysical Research 88:7617–7622
Hart BS, Long BF (1990) Recent evolution of the Outardes Estuary, Quebec, Canada: consequences of dam construction on the river. Sedimentology 37:495–507
Hartig EK, Gornitz V, Kolker A, Mushacke F, Fallon D (2002) Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City. Wetlands 22:71–89
Harvey N (1986) The Great Barrier Reef: shallow seismic investigations. Department of Geography, James Cook University of North Queensland, Monograph Series No. 14
Harvey N, Belperio AP (1994) Implications of climatic change for the South Australian coast. Transactions of the Royal Society of South Australia 118(1):45–52
Harvey N, Caton B (2003) Coastal management in Australia. Oxford University Press
Harvey N, Clouston B, Carvalho P (1999) Improving coastal vulnerability assessment methodologies for integrated coastal management: an approach from South Australia. Australian Geographical Studies 37(1):50–69
Harvey N, Belperio AP, Bourman R, Mitchell W (2002) Geologic, isostatic and anthropogenic signals affecting sea level records at tide gauge sites in southern Australia. Global and Planetary Change 32:1–11
Hay WH (1994) Pleistocene-Holocene fluxes are not the earth's norm. In: Hay WH (ed) Global sedimentary geofluxes. National Academy of Sciences Press, Washington, pp 15–27
Hayes MO (1967) Relationship between coastal climate and bottom sediment type on the inner continental shelf. Marine Geology 5: 111–132
Hayes, MO (1980) General morphology and sediment patterns in tidal inlets. Sedimentary Geology 26:139–156
Hesp PA (1984a) The formation of sand "beach ridges" and foredunes. Search 15(9–10):289–291
Hesp PA (1984b) Aspects of the geomorphology of south-western Australian estuaries. In: Hodgkin EP (Ed) Estuarine environments of the Southern Hemisphere. WA Dept of Conservation and Environment Bulletin 161
Hesp PA (1993) Late Quaternary coastal geomorphology of the South Sydney-Illawarra coast. In: Thoms M (ed) Catchments and coasts. Dept of Geography, University of Sydney Research Monograph No. 5:72–87
Hesp PA, Short AD (1999) Barrier morphodynamics. In: Short AD (ed) Handbook of beach and shoreface morphodynamics. John Wiley, pp 307–333
Hesp PA, Thom BG (1990) Geomorphology and evolution of active transgressive dunefields. In: Nordstrom KF, Psuty NP, Carter RWG (eds) Coastal dunes: form and process. John Wiley and Sons, London, pp 253–288
Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Journal of Marine and Freshwater Research 50:839–866
Holeman JN (1980) Erosion rates in the US estimated from the Soil Conservation Services inventory. EOS (Transactions of the AGU) 61:954
Holligan PM, de Boois H (1993) Land-Ocean Interactions in the Coastal Zone, Science Plan, International Geosphere-Biosphere Programme, Report No. 25
Houghton JT, Jenkins GJ, Ephraums JJ (1991) Climatic change. The IPCC scientific assessment. Cambridge University Press
Houghton JT, Callender BA, Varney SK (1992) Climatic change 1992. The supplementary report to the IPCC assessment. Cambridge University Press
Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenburg A, Maskell K (eds) (1996) Climatic change 1995: The science of climate change. Published for the IPCC by Cambridge University Press
Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001) Climate change 2001: the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). New York, Cambridge University Press
Hu D, Saito Y, Kempe S (1998) Sediment and nutrient transport to the coastal zone. In: Galloway JN, Melillo JM (eds) Asian change in the context of global climate change: Impact of natural and anthropogenic changes in Asia on global biogeochemical cycles. Cambridge University Press, IGBP Publication Series 3, 245–270
Hubbert GD, McInnes K (1999) A storm surge inundation model for coastal planning and impact studies. Journal of Coastal Research 15:168–185

Huettel M, Gust G (1992) Solute release mechanisms from confined sediment cores in stirred benthic chambers and flume flows. Marine Ecology Progress Series 82:187–197

Huettel M, Rusch A (2000) Transport and degradation of phytoplankton in permeable sediment. Limnology and Oceanography 45:534–549

Huettel M, Ziebis W, Forster S (1996) Flow-induced uptake of particulate matter in permeable sediments. Limnology and Oceanography 41:309–322

Huettel M, Ziebis W, Forster S, Luther G (1998) Advective transport affecting metal and nutrient distribution and interfacial fluxes in permeable sediments. Geochimica y Cosmochimica Acta 62: 613–631

Huntington HP (2000) Native observations capture impacts of sea ice changes. Witness the Arctic 8:1–2

Huntley DJ, Hutton JT, Prescott JR (1993) The stranded beach-dune sequence of south-east South Australia: A test of thermoluminescence dating, 0–800 ka. Quaternary Science Reviews 12:1–20

Huntley DJ, Hutton JT, Prescott JR (1994) Further thermoluminescence dates for the dune sequence in the south-east of South Australia. Quaternary Science Reviews 13:201–207

Huntley D, Leeks G, Walling D (eds) (2001) Land ocean interaction measuring and modelling fluxes from river basins to coastal seas. IWA Publishing

Hutchinson PA, Webster IT (1998) Solute uptake in aquatic sediments due to current-obstacle interactions. Journal of Environmental Engineering 124:419–426

Illenburger K, Rust I (1988) A sand budget for the Alexandria coastal dunefield, South Africa. Sedimentology 35:513–521

Inman DL, Jenkins SA (1999) Climate change and the episodicity of sediment flux of small California rivers. Journal of Geology 107: 251–270

Intergovernmental Panel on Climate Change (IPCC) (1991) Common methodology for assessing vulnerability to sea-level rise. IPCC Coastal Zone Management Subgroup, Ministry of Transport and Public Works, The Hague, The Netherlands

Intergovernmental Panel on Climate Change (IPCC) (1992) Global climate change and the rising challenge of the sea. Report of the Coastal Zone Management Subgroup, Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands

Intergovernmental Panel on Climate Change (IPCC) (1994) Preparing to meet the coastal challenges of the 21st century. Report of the world coast conference, 1–5 November 1993. Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands

Jackson JA (ed) (1997) Glossary of Geology, 4th edn. American Geological Institute, Alexandria, VA

Jahnke R, Nelson JR, Marinelli RL, Eckman JE (2000) Benthic flux of biogenic elements on the southeastern US continental shelf: influence of pore water advective transport and benthic microalgae. Continental Shelf Research 20:109–127

Jelgersma S, De Jong JD, Zagwijn WH, Van Regteren Altena JF (1970) The coastal dunes of the western Netherlands: geology, vegetational history and archaeology. In: Mededelingen Rijks Geologische Dienst, 21, pp 93–167. Rijks Geologische Dienst, Haarlem.

Jennings JN (1967) Cliff-top dunes. Australian Geographical Studies 5(1):40–49

Jia JJ, Gao S, Xue YC (2003) Sediment dynamics of small tidal inlets: an example from Yuehu Inlet, Shandong Peninsula, China. Estuarine, Coastal and Shelf Science 57(5–6):783–801

Jickells TD (1998) Nutrient biogeochemistry of the coastal zone. Science 281:217–222

Jiménez JA, Sánchez-Arcilla A (1993) Medium-term coastal response at the Ebro Delta, Spain. Marine Geology 114:105–118

Jiménez JA, Sánchez-Arcilla A (1997) Physical impacts of climatic change on deltaic coastal systems (II): driving terms. Climatic Change 35(1):95–118

Jing L, Ridd PV, Mayocchi CL, Heron ML (1996) Wave-induced benthic velocity variations in shallow waters. Estuarine and Coastal Shelf Science 42:787–802

Johannes RE (1980) The ecological significance of the submarine discharge of groundwater. Marine Ecology Progress Series 3: 365–373

Johnson MA, Polyakov IV (2001) The Laptev Sea as a source for recent Arctic Ocean salinity changes. Geophysical Research Letters 28:2017–2020

Kairu K, Nyandwi N (eds) (2000) Guidelines for the study of shoreline change in the Western Indian Ocean region. IOC Manuals and Guides No. 40. UNESCO, Paris

Kearney MS (2001) Late Holocene sea level variation. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise: history and consequences. Academic Press International Geophysics Series vol 75, pp 13–36

Klein RJT, Nicholls RJ (1999) Assessment of coastal vulnerability to climate change. Ambio 28:182–187

Klein RJT, Buckley EN, Nicholls RJ, Ragoonaden S, Aston J, Capobianco M, Mizutani M, Nunn PD (2000) Coastal adaptation. In: Metz B, Davidson OR, Martens JW, van Rooijen SN, van Wie McGrory L (eds) Methodologies and technological issues in technology transfer. A special report of IPCC Working Group III, Cambridge University Press, Cambridge, UK, pp 349–372

Kleypas JA, Buddemeier RW, Archer D, Gattuso J, Landon C, Opdyke BN (1999) Geochemical consequences of increased carbon dioxide in coral reefs. Science 284:118–120

Klijn JA (1990) The younger dunes in the Netherlands; chronology and causation. In: Bakker ThW, Jungerius PD, Klijn JA (ed) Dunes of the European coasts: geomorphology – hydrology – soils. Catena Supplement 18:89–100

Knox JC (1993) Large increase in flood magnitude in response to modest changes in climate. Nature 361:430–432

Kohout FA (1966) Submarine springs: a neglected phenomenon of coastal hydrology. Hydrology 26:391–413

Komar PD (1998b) The 1997–98 El Niño and erosion on the Oregon coast. Shore and Beach 66(3):33–41

Krest JM, Moore WS, Gardner LR, Morris J (2000) Marsh nutrient export supplied by groundwater discharge: evidence from Ra measurements. Global Biogeochemical Cycles 14:167–176

Lambeck K, Nakada M (1990) Late Pleistocene and Holocene sea-level change along the Australian coast. Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section) 89:143–176

Lambeck K, Smither C, Ekman M (1998) Tests of glacial rebound models for Fennoscandinavia based on instrumented sea- and lake-level records. Geophysical Journal International 135: 375–387

Lammers RB, Shiklomanov AI, Vorosmarty CJ, Fekete BM, Peterson BJ (2001) Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research-Atmospheres 106:3321–3334

Le Floch J (1961) Propagation de la marée dans l'estuaire de la Seine et en Seine Maritime, DSc thesis, Université de Paris

Leatherman SP (2001) Social and economic costs of sea level rise. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise: history and consequences. International Geophysics Series, vol 75. Academic Press, San Diego, London

Leatherman SP, Zhang K, Douglas BC (2000) Sea level rise shown to drive coastal erosion. EOS 81(6):55–57

Lee SY, Holder GD (2001) Methane hydrates potential as a future energy source. Fuel Processing Technology 71:181–186

Lewis AG, Syvitski JPM (1983) Interaction of plankton and suspended sediment in fjords: Sedimentary Geology 36:81–92

Li L, Barry DA, Stagnitti F, Parlange JY (1999) Submarine groundwater discharge and associated chemical input to a coastal sea. Water Resources Research 35:3253–3259

Lohse L, Epping EHG, Helder W, van Raaphorst WR (1996) Oxygen porewater profiles in continental shelf sediments of the North Sea – turbulent versus molecular diffusion. Marine Ecology Progress Series 145:63–75

Loope WL, Arbogast AF (2000) Dominance of a ~150 year cycle of sand supply change in late Holocene dune-building along the eastern shore of Lake Michigan. Quaternary Research 54: 414–422

MacIntyre IB, Nurke RB, Stuckenrath R (1977) Thickest recorded Holocene reef section, Isla Periez core hole, Alacran Reef, Mexico. Geology 5:749–754

Madej MA, Ozaki V (1996) Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21(10):911–927

Marinelli RL, Jahnke RA, Craven DB, Nelson JR, Eckman JE (1998) Sediment nutrient dynamics on the South Atlantic Bight continental shelf. Limnology and Oceanography 43: 1305–1320

Marsh JA (1977) Terrestrial inputs of nitrogen and phosphates on fringing reefs on Guam. Proceedings Third International Coral Reef Symposium, pp 331–336

McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) (2001) Climate change 2001: impacts, adaptation and vulnerability – contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). New York, Cambridge University Press

McLaughlin CJ, Smith, CA, Buddemeier RW, Bartley JD, Maxwell BA (2003) Rivers, runoff and reefs. Global and Planetary Change 39:191–199

McLean RF, Mimura N (eds) (1993) Vulnerability assessment to sea-level rise and coastal zone management. Proceedings of the IPCC Eastern Hemisphere Workshop, Tokyo

Meade RH (1996) River-sediment inputs to major deltas. In: Milliman JD, Haq BU (eds) Sea-level rise and coastal subsidence. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 63–85

Meade RH, Yuzyk TR, Day TJ (1990) Movement and storage of sediment in rivers of the United States and Canada. In: Wolman MG, Riggs HC (eds) Surface water hydrology. The geology of North America, v. O-1, Geological Society of America, Boulder CO, pp 255–280

Milliman JD, Syvitski JPM (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology 100(5):525–544

Milliman JD, Qin YS, Ren MEY (1987) Man's influence on the erosion and transport of sediment by Asian rivers: The Yellow River (Huanghe) example. Journal of Geology 95:751–762

Milliman JD, Haq BU (eds) (1996) Sea-level rise and coastal subsidence: causes, consequences and strategies. Kluwer Academic Publishers, Dordrecht, The Netherlands

Mitchell W, Chittleborough J, Ronai B, Lennon GW (2001) Sea level rise in Australia and the Pacific. In: Grzechnik M, Chittleborough J (eds) Proceedings of the Pacific Islands conference on climate change, climate variability and sea level rise: linking science and policy, Rarotonga, Cook Islands, 3–7 April 2000, National Tidal Facility Australia, Adelaide

Mitrovica JX, Davis JL (1995) Present-day post-glacial sea level change far from the late Pleistocene ice sheets: implications for recent analyses of tide-gauge records. Geophysical Research Letters 22:2529–2532

Moore WS (1996) Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments. Nature 380:612–614

Moore WS (1999) The subterranean estuary: a reaction zone of groundwater and seawater. Marine Chemistry 65:111–126

Morehead MD, Syvitski JPM, Hutton EWH, Peckham SD (2003) Modeling the inter-annual and intra-annual variability in the flux of sediment in ungauged river basins. Global and Planetary Change 39:95–110

Morison J, Aagaard K, Steele M (2000) Recent environmental changes in the Arctic: a review. Arctic 53:359–371

Moritz RE, Aagaard K, Baker DJ, Codispoti LA, Smith SL, Smith WO, Tipper RC, Walsh JE (1990) Arctic system science: ocean-atmosphere-ice interactions. Joint Oceanographic Institutions Inc., Washington DC

Mulder T, Syvitski JPM (1995) Turbidity currents generated at river mouths during exceptional discharge to the world oceans. Journal of Geology 103:285–298

Nairn RB, Solomon S, Kobayashi N, Virdrine J (1998) Development and testing of a thermal-mechanical model for predicting Arctic shore erosion processes. In: Lewkowicz AG, Allard M (eds) Permafrost: Proceedings of the Seventh International Conference, Yellowknife, NWT, June 23–27 Centre d'études nordiquies, Universite Laval, Quebec, Canada, pp 789–795

Naki-enovi N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Raihi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC Special report on emissions scenarios. Cambridge University Press, Cambridge, UK and New York, NY, USA

Nelson JR, Eckman JE, Robertson CY, Marinelli RI, Jahnke RA (1999) Benthic microalgal biomass and irradiance at the sea floor on the continental shelf of the South Atlantic Bight: spatial and temporal variability and storm effects. Continental Shelf Research 19:477–505

Nerem RS, Mitchum GT (2001) Observations of sea level change from satellite altimetry. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise: history and consequences. Academic Press, International Geophysics Series, vol 75, pp 121–163

Nicholls RJ (2002) Analysis of global impacts of sea-level rise: a case study of flooding. Physics and Chemistry of the Earth, Parts A/B/C 27(32–34):1455–1466

Nicholls RJ, Branson J (1998) Coastal resilience and planning for an uncertain future: an introduction. Geographical Journal 164: 255–258

Nicholls RJ, de la Vega-Leinert A (2001) The SURVAS project at the Overview Workshop. In: de la Vega-Leinert A, Nicholls RJ (eds) Proceedings of the SURVAS Overview Workshop on the future of vulnerability and adaptation studies. The Royal Chace, London

Nicholls RJ, Leatherman SP (eds) (1995) Potential impacts of accelerated sea level rise on developing countries. Journal of Coastal Research Special Issue 14

Nicholls RJ, Hoozemans FMJ, Marchand M (1999) Increasing flood risk and wetland losses due to sea-level rise: regional and global analyses. Global Environmental Change 9:S69–S87

Nielsen P (1990) Tidal dynamics in the water table in a beach. Water Resources Research 26:2127–2134

Nittrouer, CA, DeMaster, DJ (1986) Sedimentary processes on the Amazon continental shelf: past, present and future research. Continental Shelf Research 6:5–30

Nittrouer CA, Wright LD (1994) Transport of particles across continental shelves. Reviews of Geophysics 32:85–113

Nixon SW (2003) Replacing the Nile: are anthropogenic nutrients providing the fertility once brought to the Mediterranean by a great river? Ambio 32 (1):30–39

Opsahl S, Benner R, Ammon RMW (1999) Major flux of terrigenous dissolved organic matter through the Arctic Ocean. Limnology and Oceanography 44:2017–2023

Paerl HW (1997) Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. Limnology and Oceanography 42:1154–1165

Pasternack GB, Brush GS, Hilgartner WB (2001) Impact of historic land-use change on sediment delivery to a Chesapeake Bay subestuarine delta. Earth Surface Processes and Landforms 26: 409–427

Paull CK, Speiss F, Curry J, Twichell D (1990) Origin of Florida Canyon and the role of spring sapping on the formation of submarine box canyons. Geological Society of America Bulletin 102: 502–515

Peltier WR (1996) Global sea level rise and glacial isostatic adjustment: an analysis of data from the east coast of North America. Geophysical Research Letters 23:717–720

Peltier WR (2001) Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Douglas BC, Kearney MS, Leatherman SP (eds) Sea level rise: history and consequences. Academic Press, San Diego, CA, pp 65–95

Peltier WR (2002) On eustatic sea level history: last glacial maximum to Holocene. Quaternary Science Reviews 21:377–396

Peltier WR, Jiang X (1997) Mantle viscosity, glacial isostatic adjustment and the eustatic level of the sea. Surveys in Geophysics 18: 239–277

Peltier WR, Tushingham AM (1989) Global sea level rise and the greenhouse effect: might they be connected? Science 244: 806–810

Peltier WR, Tushingham AM (1991) Influence of glacial isostatic adjustment on tide gauge measurements of secular sea level change. Journal of Geophysical Research 96:6779–6796
Perillo GME (1995) Definition and geomorphologic classifications of estuaries. In Perillo GME (ed) Geomorphology and sedimentology of estuaries. Developments in Sedimentology 53:17–47, Elsevier Science BV, Amsterdam
Perillo GME (2000) Sediment budgets and fluxes in estuarine and coastal areas. IGBP-LOICZ Water Workshop, Boulder, CO (oral presentation)
Pernetta JC, Milliman JD (1995) Land-Ocean Interactions in the Coastal Zone, implementation plan. International Geosphere-Biosphere Programme, Report No. 33
Pethick J (2001) The Anglian coast. In von Bodungen B and Turner RK (eds) Science and integrated coastal management. Dahlem Workshop Report 85, Dahlem University Press, Berlin, pp 121–134
Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Bender, M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pépin L, Ritz C, Saltzman E, Stievenard M (1999) Climate and atmospheric history of the past 420 000 years from the Vostok ice core, Antarctica. Nature 399:429–436
Pfirman S, Gascard J-C, Wollenburg I, Mudie P, Abelman A (1989) Particle-laden Eurasian Arctic sea ice: observations from July and August 1987. Polar Research 7:59–66
Pfirman S, Colony R, Nürnberg D, Eicken H, Rigor I (1997) Reconstructing the origin and trajectory of drifting Arctic sea ice. Journal of Geophysical Research 102 C6):12575–12586
Plant GW, Covil CS, Hughes RA (eds) (1998). Site preparation for the New Hong Kong International Airport. Thomas Telford, London
Plummer LN (1975) Mixing of seawater with calcium carbonate ground water. In: Whitten EHT (ed) Quantitative studies in the geological sciences. Geological Society of America Memoir 85, pp 219–238
Proshutinsky A, Polyakov IV, Johnson MA (1999) Climate states and variability of Arctic ice and water dynamics during 1946–1997. Polar Research 18:1–8
Psuty NP (1992) Spatial variation in coastal foredune development. In Carter RWG, Curtis TGF, Sheehy-Skeffington MJ (eds) Coastal dunes. AA Balkema, Rotterdam, pp 3–13
Pye K (1983) Coastal dunes. Progress in Physical Geography 7(4): 531–557
Pye K, Bowman GM (1984) The Holocene marine transgression as a forcing function in episodic dune activity on the eastern Australian coast. In: Thom BG (ed) Coastal geomorphology in Australia. Academic Press, pp 179–196
Qian CL (1994) The impacts of water withdrawal from Luanhe River on the delta. Acta Geographica Sinica 49:158–166 (in Chinese)
Rabalais NN, Turner RE, Dortch Q, Justic D, Bierman VJ, Wiseman WJ (2002) Nutrient-enhanced productivity in the northern Gulf of Mexico: past, present and future. Hydrobiologia 475/476:39–63
Rachold V, Grigoriev MN, Are FE, Solomon S, Reimnitz E, Kassens H, Antonow M (2000) Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas. International Journal of Earth Sciences 89:450–460
Raynaud D, Barnola J-M, Chappellaz J, Blunier T, Indermühle A, Stauffer B (2000) The ice record of greenhouse gases: a view in the context of future changes. Quaternary Science Reviews 19:9–17
Reay WG, Gallagher DL, Simmons GM (1992) Groundwater discharge and its impact on surface water quality in a Chesapeake Bay inlet. Water Research Bulletin 28:1121–1134
Reich CD, Shinn EA, Hickey TD, Tihansky AB (2002) Tidal and meteorological influences on shallow marine groundwater flow in the upper Florida Keys. In: Porter JW, Porter KG (eds) The Everglades, Florida Bay, and coral reefs of the Florida Keys, CRC Press, Boca Raton, pp 659–676
Reimnitz E, McCormick M, McDongall K, Brouwers E (1993) Sediment export by ice rafting from a coastal polynya, Arctic Alaska, USA. Arctic and Alpine Research 25:83–98
Restrepo JD, Kjerfve B, Correa ID, González JL (2002) Morphodynamics of a high discharge tropical delta, San Juan River, Pacific coast of Colombia. Marine Geology 192: 355–381
Riedl R, Huang N, Machan R (1972) The subtidal pump: a mechanism of interstitial water exchange by wave action. Marine Biology 13:210–221
Ritchie W, Penland S (1990) Aeolian sand bodies of the south Louisiana coast. In: Nordstrom KF, Psuty NP, Carter RWG (eds) Coastal dunes form and process. John Wiley and Sons, London, pp 105–127
Romankevich EA, Vetrov AA, Vinogradov ME, Vedernikov VI (2000) Carbon cycling components in the Arctic seas of Russia: carbon fluxes from land, carbon in the bottom sediments, elements of balance. Oceanology 40:335–344
Rothrock DA, Yu Y, Maykut GA (1999) Thinning of the Arctic sea-ice cover. Geophysical Research Letters 26:3469–3472
Rouse WR (2000) The energy and water balance of high-latitude wetlands: controls and extrapolation. Global Change Biology 6: 59–68
Runnels DD (1969) Diagenesis, chemical sediments, and mixing of natural waters. Journal of Sedimentary Petrology 39:1188–1201
Sabhasri S, Suwanarat K (1996) Impact of sea level rise on flood control in Bangkok and vicinity. In: Milliman JD, Haq BU (eds) Sea-level rise and coastal subsidence: causes, consequences and strategies. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 343–356
Saito Y (2001) Deltas in Southeast and East Asia: their evolution and current problems. In: Mimura N, Yokoki H (eds) Global change and Asia Pacific coast. Proceedings of APN/SURVAS/LOICZ joint conference on coastal impacts of climate change and adaptation in the Asia-Pacific Region, APN, Kobe, Japan, pp 185–191
Saito Y, Ikehara K, Katayama H, Matsumoto E, Yang Z (1994) Course shift and sediment discharge changes of the Huanghe recorded in sediments of the East China Sea. Chishitsu News 476:8–16
Saito Y, Yang ZS, Hori K (2001) The Huanghe (Yellow River) and Changjiang (Yangtze) deltas: a review on their characteristics, evolution and sediment discharge during the Holocene. Geomorphology 41:219–231
Salisbury JE, Campbell JW, Meeker LD, Vörösmarty C (2001) Ocean color and river data reveal fluvial influence in coastal waters. EOS 82(20):226–227
Salisbury JE, Campbell JW, Linder EL, Meeker D, Müller-Karger FE, Vörösmarty CJ (2004) On the seasonal correlation of surface particle fields with wind stress and Mississippi discharge in the northern Gulf of Mexico. Deep Sea Research II 51:1187–1203
Sánchez-Arcilla A, Jiménez JA, Valdemoro HI (1998) The Ebro delta: morphodynamics and vulnerability. Journal of Coastal Research 14(3):754–772
Saunders KE, Davidson-Arnott RGD (1990) Coastal dune response to natural disturbances. Canadian Symposium on Coastal Sand Dunes, pp 321–345
Schanck EJ, Fasano JL, Lanferedi NW, Pousa JL (1990) Impacts of sea level rise on the Argentine coast. In: Changing climate and the coast. IPCC Report 2, UNEP-WMOO-USACE-EPA-NOAA, pp 363–384
Schlager W (1999) Scaling of sedimentation rates and drowning of reefs and carbonate platforms. Geology 27:183–186
Semiletov IP (1999) On aquatic sources and sinks of CO_2 and CH_4 in the Polar regions. Journal of Atmospheric Sciences 56:286–306
Semiletov IP, Savelieva NI, Weller GE (2001) Cause and effect linkages between atmosphere, the Siberian rivers and conditions in the Russian Shelf seas. In: Semiletov IP (ed) Changes in the atmosphere-land-sea system in the Amerasian Arctic, pp 63–96
Serreze MC, Walsh JE, Chapin FSI, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel WC, Morison J, Zhang T, Barry RG (2000) Observational evidence of recent change in the northern high-latitude environment. Climate Change 46:159–209
Shennan I, Woodworth PL (1992) A comparison of late Holocene and twentieth-century sea level trends from the UK and North Sea region. Geophysical Journal International 109:96–105
Short AD (1987) Modes, timing and volume of Holocene cross-shore and aeolian sediment transport, Southern Australia. ASCE, Proceedings of Coastal Sediments '87, pp 1925–1937
Short AD (1988a) Response of a high through low energy sandy coast to sea-level transgression and stillstand, South Australia. Geographical Review 78:119–136

Short AD (1988b) Holocene coastal dune formation in southern Australia – a case study. Sedimentary Geology 55:121–142

Shulmeister J, Short SA, Price DM, Murray AS (1993) Pedogenic uranium/thorium and thermoluminescence chronologies and evolutionary history of a coastal dunefield, Groote Eylandt, northern Australia. Geomorphology 8:47–64

Shum KT, Sundby B (1996) Organic matter processing in continental shelf sediments – the subtidal pump revisited. Marine Chemistry 53:81–87

Simmons GM Jr (1992) Importance of submarine groundwater discharge (SGWD) and seawater cycling to material flux across sediment/water interfaces in marine environments. Marine Ecology Progress Series 84:173–184

Simmonds I, Keay K (2000) Variability of southern hemisphere extratropical cyclone behavior, 1958–97. Journal of Climate 13: 550–561

Skirving W, Guinotte J (2001) The sea surface temperature story on the Great Barrier Reef during the coral bleaching event of 1998. In Wolanski E (ed) Oceanographic processes of coral reefs. Physical and biological links in the Great Barrier Reef. CRC Press LLC, Boca Raton, Florida, pp 301–309

Smith SV, Renwick WH, Buddemeier RW, Crossland CJ (2001) Budgets of soil erosion and deposition for sediment and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15(3):697–707

Smithers SG, Woodroffe CD (2000) Microatolls as sea-level indicators on a mid-ocean atoll. Marine Geology 168:61–78

Snoussi M, Haida S, Imassi S (2002) Effects of the construction of dams on the Moulouya and the Sebou rivers (Morocco). Regional Environmental Change 3:5–12

Solomon SM, Forbes DL, Kierstead B (1994) Coastal impacts of climate change: Beaufort Sea erosion study. Canadian Climate Centre Report 94-2. Environment Canada, Downsview Ontario, Canada

Speer PE, Aubrey DG. (1985) A study of non-linear tidal propagation in shallow inlet/estuarine systems, Part II: Theory. Estuarine, Coastal and Shelf Science 21:207–224

Spencer T, Tudhope AW, French JR, Scoffin TP, Utanga A (1997) Reconstructing sea level change from coral microatolls, Tongareva (Penryn) Atoll, Northern Cook Islands. Proceedings of the 8th International Coral Reef Symposium 1:489–494

Stanley DJ, Warne AG (1993) Nile Delta: recent geological evolution and human impact. Science 260:628–634

Steffen W, Jager J, Carson DJ, Bradshaw C eds. (2003) Challenges of a changing earth. Proceedings of the Global Change Open Science Conference, Amsterdam, The Netherlands, 10–13 July 2001. Springer Verlag, Heidelberg, Germany

Stierle AP, Eicken H (2002) Sedimentary inclusions in Alaskan coastal sea ice: small-scale distribution, interannual variability and entrainment requirements. Arctic Antarctic and Alpine Research 34:465–476

Stoddart DR (1969) World erosion and sedimentation. In: Chorley RJ (ed) Water, earth and man. Methuen Co. Ltd, London, pp 43–64

Sunrise Technical Consultants (1968) Estudio mediante ensayo hidráulico sobre modelo del Puerto de Mar del Plata y sus alrededores. vol I–VIII, Tokyo, Japan

Syvitski JPM (2002) Sediment transport variability in Arctic Rivers: implications for a warmer future. Polar Research 21(2):323–330

Syvitski JPM (2003a) Sediment fluxes and rates of sedimentation. In: Middleton GV (ed) Encyclopedia of sediments and sedimentary rocks. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 600–606

Syvitski, JPM (2003b) The influence of climate on the flux of sediment to the coastal ocean. Proceedings of OCEANS 2003, San Diego, Holland Publishing, pp 496–502

Syvitski, JPM (2003c) Supply and flux of sediment along hydrological pathways: research for the 21st century. Global and Planetary Change 39:1–11

Syvitski JPM, Morehead MD (1999) Estimating river-sediment discharge to the ocean: application to the Eel Margin, northern California. Marine Geology 154:13–28

Syvitski JPM, Nicholson M, Skene K, Morehead MD (1998) PLUME1.1: Deposition of sediment from a fluvial plume. Computers and Geoscience 24(2):159–171

Syvitski, JPM, Peckham SD, Hilberman RD, Mulder T (2003) Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. Sedimentary Geology 162:5–24

Ta TKO, Nguyen VL, Tateishi M, Kobayashi I, Tanabe S, Saito Y (2002) Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. Quaternary Science Reviews 21: 1807–1819

Taniguchi M, Burnett WC, Cable JE, Turner JV (2002) Investigation of submarine groundwater discharge. Hydrological Processes 16:2115–2129

Thibodeaux LJ, Boyle JD (1987) Bedform-generated convective transport in bottom sediment. Nature 325:341–343

Thieler RE, Hammar-Klose ES (1999) National assessment of coastal vulnerability to sea-level rise: US Atlantic Coast. USGS, Woods Hole, MA

Thieler ER, Hammar-Klose ES (2000) National assessment of coastal vulnerability to sea level rise: preliminary results for the US Gulf of Mexico coast. USGS Open-File Report 00-179

Thom BG, Bowman GM, Roy PS (1981) Late Quaternary evolution of coastal sand barriers, Port Stephens-Myall Lakes area, central NSW, Australia. Quaternary Research 15:345–364

Thom BG, Shepherd MJ, Ly C, Roy P, Bowman GM, Hesp PA (1992) Coastal geomorphology and Quaternary geology of the Port Stephens- Myall Lakes area. Department of Biogeography and Geomorphology, ANU, Monograph No. 6, ANUTech PL, Canberra

Thom BG, Hesp PA, Bryant T (1994) Last glacial "coastal dunes" in eastern Australia and implications for landscape stability during the Last Glacial Maximum. Palaeogeography, Palaeoclimatology, Palaeoecology 111:229–248.

Thorstenson DC, Mackenzie FT (1974) Time variability of porewater chemistry in recent carbon sediments, Devil's Hole, Harrington, Sound Bermuda. Geochemica Cosmochimica Acta 38:1–19

Titus JG (1998) Rising seas, coastal erosion and the takings clause: how to save wetlands and beaches without hurting property owners. Maryland Law Review 57:1279–1399

Titus JG, Richman C (2001) Maps of lands vulnerable to sea level rise: modeled elevations along the US Atlantic and Gulf Coasts. Climate Research 18:205–228

Tovey NK, Yim WW-S (2002) Desiccation of late Quaternary inner shelf sediments of Hong Kong: microfabric observations. Quaternary International 92:73–87

Trupin A, Wahr J (1990) Spectroscopic analysis of global tide gauge sea level data. Geophysical Journal International 100:441–453

Tynan CT, Demaster DP (1997) Observations and predictions of Arctic climatic change: potential effects on marine mammals. Arctic 50:308–322

Umezawa Y, Miyajima T, Kayanne H, Koike I (2002) Significance of groundwater nitrogen discharge into coral reefs at Ishigaki Island, southwest of Japan. Coral Reefs 21(4):346–356

UNEP (1998) East Africa atlas of coastal resources – Kenya. UNEP, Nairobi

UNEP (2001) East Africa Atlas of Coastal Resources – Tanzania. UNEP, Nairobi

Valiela I, Costa J, Foreman K, Teal JM, Howes B, Aubrey D (1990) Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters. Biogeochemistry10:177–197

Vörösmarty CJ, Meybeck M, Fekete B, Sharma K (1997) The potential impact of neo-Castorization on sediment transport by the global network of rivers. In: Walling DE, Probst J-L (eds) Human impact on erosion and sedimentation. IAHS Publication No. 245, pp 261–273

WASA (1998) Changing waves and storms in the Northeast Atlantic. Bulletin of the American Meteorological Society 79:741–760

Walling DE, Fan D (2003) Recent trends in the suspended sediment loads of the world's rivers. Global and Planetary Change 39: 111–126

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395

Wang Y, Ren M-e, Syvitski JPM (1998) Sediment transport and terrigenous fluxes. In: Brink KH, Robinson AR (eds) The Sea; vol 10: the global coastal ocean: processes and methods. John Wiley & Sons, New York, pp 253–292

Wasson RJ (1996) Land use and climate impacts on fluvial systems during the period of agriculture. PAGES Workshop Report, Series 96-2
Watson RT, Zinyowera MC, Moss RH, Dokken DJ (1996) Technical summary: impacts, adaptations and mitigation options. In: Watson RT, Zinyowera MC, Moss RH (eds) Climatic change 1995 – impacts, adaptations and mitigation of climate change: scientific-technical analyses. Preparing for a changing climate: the potential consequences of climate variability and change – mid Atlantic foundations. January 2001. Cambridge University Press, New York, pp 19–53
Watson RT, Zinyowera MC, Moss RH, Dokken DJ (1998) The regional impacts of climate change: an assessment of vulnerability. A special report of IPCC Working Group II, Intergovernmental Panel on Climate Change, Cambridge University Press
Webb JE, Theodor J (1968) Irrigation of submerged marine sands through wave action. Nature 220:682–685
Wells JT (1996) Subsidence, sea-level rise, and wetland loss in the lower Mississippi River delta. In: Milliman JD, Haq BU (eds) Sea-level rise and coastal subsidence. Kluwer Academic Publishing, Dordrecht, The Netherlands, pp 281–311
Wheeler PA, Gosselin M, Sherr E, Thibault D, Kirchman DL, Benner R, Whitledge TE (1996) Active cycling of organic carbon in the central Arctic ocean. Nature 380:697–699
Wheeler PA, Watkins JM, Hansing RL (1997) Nutrients, organic carbon and organic nitrogen in the upper water column of the Arctic Ocean: implications for the sources of dissolved organic carbon. Deep-Sea Research (II) 44:1571–1592
Wiberg PL, Harris CK (1994) Ripple geometry in wave-dominated environments. Journal of Geophysical Research – Oceans 99:775–789
Wigley TLM, Raper SCB (1993) Future changes in global mean temperature and sea level. In: Warrick RA, Barrow EM, Wigley TML (eds) Climate and sea level change: observations, projections and implications. Cambridge University Press, pp 111–135
Wilkinson C (ed) (2000) Status of coral reefs of the world: 2000. Australian Institute of Marine Science, Townsville
Wolanski E (ed) (2001) Oceanographic processes of coral reefs: physical and biological links in the Great Barrier Reef. CRC Press, Florida
Wolanski E, Chappell J (1996) The response of tropical Australian estuaries to a sea level rise. Journal of Marine Systems 7:267–279
Wolanski E, Duke N (2002) Mud threat to the Great Barrier Reef of Australia. In: Healy T, Wang Y, Healy J-A (eds) Muddy coasts of the world: processes, deposits and function. Elsevier Science BV, Amsterdam, pp 533–542
Wolanski E, Spagnol S (2000) Environmental degradation by mud in tropical estuaries. Regional Environmental Change 1(3–4):152–162
Wolanski E, Spagnol S (2003) Dynamics of the turbidity maximum in King Sound, tropical Western Australia. Estuarine, Coastal and Shelf Science 56:877–890
Wolanski E, King B, Galloway D (1995) Dynamics of the turbidity maximum in the Fly River estuary, Papua New Guinea. Estuarine, Coastal and Shelf Science 40:321–337
Wolanski E, Huan NN, Dao LT, Nhan NH, Thuy NN (1996) Fine sediment dynamics in the Mekong River estuary, Vietnam. Estuarine, Coastal and Shelf Science 43:565–582
Wolanski E, Nhan NH, Spagnol S (1997) Sediment dynamics during low flow conditions in the Mekong River estuary, Vietnam. Journal of Coastal Research 13:1241–1251
Wolanski E, Moore K, Spagnol S, D'Adamo N, Pattiaratchi C (2001) Rapid, human-induced siltation of the macro-tidal Ord River estuary, Western Australia. Estuarine, Coastal and Shelf Science 53:717–732
Wolanski E, Richmond RH, Davis G, Bonito V (2003a) Water and fine sediment dynamics in transient river plumes in a small, reef-fringed bay, Guam. Estuarine, Coastal and Shelf Science 56:1–13
Wolanski E, Richmond R, McCook L, Sweatman H (2003b) Mud, marine snow and coral reefs. American Scientist 91(1):44–51
Wolanski E, Boorman LA, Chicharo L, Langlois-Saliou E, Lara R, Plater AJ, Uncles RJ, Zalewski M (2004) Ecohydrology as a new tool for sustainable management of estuaries and coastal waters. Wetlands Ecology and Management 12(4):235–276
Woodroffe CD (1990) The impact of sea-level rise on mangrove shorelines. Progress in Physical Geography 14:483–520
Woodroffe C, Gagan MK (2000) Coral microatolls from the Central Pacific record late Holocene El Nino. Geophysical Research Letters 27:1511–1514
Woodroffe C, Mclean R (1990) Microatolls and recent sea-level change on coral atolls. Nature 344:531–534
Woodroffe CD, Chappell JMA, Thom BG, Wallensky E (1986) Geomorphological dynamics and evolution of the South Alligator tidal rivers and plains, Northern Territory. Australian National University, Northern Australia Research Unit, Mangrove Monograph 3, Darwin
Woodward JC (1995) Patterns of erosion and suspended sediment yield in Mediterranean river basins. In: Foster IDL, Gurnell AM, Webb BW (eds) Sediment and water quality in river catchments. John Wiley & Sons Ltd, pp 365–389
Woodworth PL (1993) Sea level changes. In Warrick RA, Barrow EM, Wigley TML (eds) Climate and sea level change: observations, projections and implications. Cambridge University Press, pp 379–391
Woodworth PL, Tsimplis MN, Flather RA, Shennan I (1999) A review of the trends observed in British Isles mean sea level data measured by tide gauges. Geophysical Journal International 136: 651–670
Wyatt A (1986) Challinor's Dictionary of Geology, 6th edn. University of Wales Press, Cardiff
Yang ZS, Saito Y, Liu B, Zhang J, Wang HJ (2002) Decadal and millennial time-scale changes of water and sediment discharges of the Huanghe (Yellow River) caused by human activities. In: Hong GH, Kremer HH, Pacyna J, Chen C-TA, Behrendt H, Salomons W and Marshall Crossland JI (2002) East Asia Basins: LOICZ Global assessment and synthesis of river catchment-coastal sea interaction and human dimensions. LOICZ Reports & Studies No. 26, LOICZ, Texel, The Netherlands, pp 118–121
Yim WW-S (1999) Radiocarbon dating and the reconstruction of late Quaternary sea-level changes. Quaternary International 55: 77–91
Yim WW-S (2001) Stratigraphy of Quaternary offshore sand and gravel deposits in the Hong Kong SAR, China. Quaternary International 82:101–116
Yim WW-S, Choy AMSF (2000) Some engineering applications of Quaternary sea-level changes in Hong Kong. In: Proceedings, Conference on Engineering Geology Hong Kong 2000, Hong Kong. The Institution of Mining & Metallurgy, London – Hong Kong Branch, 10 November 2000, pp 211–218
Yim WW-S, Li Q-Y (1983) Sea-level changes and sea-floor surficial deposits off Chek Lap Kok. In: Yim WW-S, Burnett AD (eds) Geology of surficial deposits in Hong Kong. Abstracts No. 1, Geological Society of Hong Kong and Department of Geography & Geology, The University of Hong Kong, Hong Kong, pp 48–59
Yim WW-S, Ivanovich M, Yu K-F (1990) Young age bias of radiocarbon dates in pre-Holocene marine deposits of Hong Kong and implications for Pleistocene stratigraphy. Geo-Marine Letters 10: 165–172
Yim WW-S, Price DM, Choy AMSF (2002) Distribution of moisture contents and thermoluminescence ages in an inner shelf borehole from the new Hong Kong International Airport. Quaternary International 92:35–43
Young R, Bryant EA, Price DM, Wirth LM, Pease M (1993) Theoretical constraints and chronological evidence of Holocene coastal development in central and southern NSW, Australia. Geomorphology 7:317–329
Zektser IS (2000) Groundwater and the environment: applications for the global community. Lewis Publishers, Boca Raton
Zhang Y, Wang WC (1997) Model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario. Journal of Climate 10:1004–1020
Ziebis W, Huettel M, Forster S (1996) Impact of biogenic sediment topography on oxygen fluxes in permeable seabeds. Marine Ecology-Progress Series 140:227–237

Chapter 3

C, N, P Fluxes in the Coastal Zone

Stephen V. Smith, Robert W. Buddemeier, Fredrik Wulff, Dennis P. Swaney
Contributors: *Victor F. Camacho-Ibar, Laura T. David, Vilma C. Dupra, Joannie A Kleypas, Maria Lourdes San Diego-McGlone, Casey McLaughlin, P. Sandhei*

3.1 Introduction

Human activities have profoundly altered the global biogeochemical cycles of many elements and compounds. These changes have not only direct effects on environmental quality, in terms of ecosystem productivity, biodiversity and sustainability for human use, but also indirect effects on climate change. A major consideration in LOICZ, and indeed throughout IGBP, concerns the biogeochemical interactions among various major compartments of the Earth system. Viewing the Earth system as an array of coupled biogeochemical cycles allows us to simplify the movements of material on Earth and their couplings to climate (Jacobson et al. 2000). While many elements play a role in these biogeochemical reactions, the elements carbon, nitrogen and phosphorus stand out for several reasons:

- All three elements are required for life processes. Carbon is the basic building block of life, nitrogen is a key element in protein and phosphorus is a key element in ATP (see Schlesinger 1997, for a review of the biogeochemistry of these elements).
- All three have major global compartments (land, ocean, atmosphere) that are depleted in the open ocean by biogeochemical processes, potentially altering ecological function. For example, the atmosphere has a sufficiently low concentration of C (largely in the form of CO_2) that atmospheric concentrations vary both seasonally and inter-annually in response to global metabolism – uptake to and release from biomass (e.g., Keeling et al. 1995). Nitrogen and phosphorus are depleted to near analytical detection limits in many parts of the surface ocean (Sverdrup et al. 1942). While both carbon and nitrogen are rapidly circulated via the atmosphere, phosphorus has no significant gas phase (Schlesinger 1997).
- A long-recognised paradigm for budgeting C, N and P is that there tend to be rather well-preserved consistent composition and flux ratios among these elements for the buildup and decomposition of organic matter. Thus, information about one of the elements carries information about the other elements as well. Perhaps the best-known example of this tendency towards a constant composition ratio, or stoichiometry, is the Redfield Ratio (Redfield 1958). Planktonic organisms in the sea tend towards a constant C:N:P molar composition ratio of 106 : 16 : 1. As these organisms decompose in the water column below the photic zone, they release C, N and P in this ratio. A result is that the dissolved inorganic C, N and P content of the deep water column increases in this ratio (see also Takahashi et al. 1985, Watson and Whitfield 1985).
- Environmental changes associated with human activities are altering the abundance of these elements in one or more of the major global compartments. For example, fossil fuel and biomass burning liberates CO_2 and elevates the atmospheric concentrations (Prentice et al. 2001). Discharge of waste products from human activities elevates concentrations of all of these elements in surface waters (Meybeck 1982, Meybeck et al. 1989). Land-use practices associated with activities such as agriculture, deforestation, dam construction and urban development also alter these concentrations, resulting in dramatic disruptions of coastal and estuarine ecosystems (Cooper and Brush 1991, Caraco and Cole 1999, Rabalais et al. 2002).
- Fundamental differences in the geochemical processes of C, N and P control how these elements are distributed between gas, solid and dissolved inorganic and organic phases in water, sediments and soils (Schlesinger 1997). Changes in their relative proportions may further enhance eutrophication by favoring noxious and harmful algal blooms (Officer and Ryther 1980, Smayda 1990, Conley et al. 1993, Justic et al. 1995, Dortch et al. 2001, Rabalais et al. 2002, Smith et al. 2003).

Other elemental constituents are also important. For example, silicon (Si), if limiting, may change the compositions of phytoplankton and the entire food web (Officer and Ryther 1980, Turner et al. 1998, Humborg et al. 2000). Iron (Fe) may in some oceanic regions limit overall primary productivity or certain taxa (cyanobacteria) (see Boyd and Doney 2003).

Many inventories or models of the Earth system simply treat the coastal zone as an integral part of larger land, ocean and atmosphere compartments (e.g., Schlesinger 1997, Prentice et al. 2001). Such a simple division is heuristically persuasive, and indeed many traditional university earth science departments are organised roughly along these lines. Such a division, carried to the extreme in models and inventories, misses important information discussed below and in Sect. 3.2.

3.1.1 The Coastal Zone and Fluxes

There is no well-defined boundary between the land and ocean in terms of global biogeochemical function. Human population density and many activities associated with humans show strong gradients of change near the coastline. About half the world's population, most of the world's large cities, much of the world's agriculture, and a high proportion of the infrastructure associated with transport lie within about 100 km of the coastline (Scialabba 1998, WRI 2000). While humans are, for the most part, constrained to live on the landward side of the coast compartment, the zone of intense human activity and influence crosses it. Aquaculture, fisheries, marine transport, mineral extraction and other human activities occur along the continuum of the coastal compartment and generally decrease with distance from the coastline.

Within the coastal ocean, the sea floor is a second important component. Organisms live there, in abundance. Organic material, either produced in the coastal ocean or delivered from outside (from land, largely via rivers; from the ocean, largely via upwelling), settles on the bottom and decomposes there. This sets up strong chemical reactions leading to oxygen depletion and gradients (especially oxygen) in the water column and into the sediments. These gradients profoundly influence the chemistry of material decomposition, regeneration and flux (Reeburgh 1983, Seitzinger 1988, Canfield 1989).

With distance away from the coastline, human influence diminishes and water becomes deeper. Biogeochemical processes become dominated by the water column with relatively little land and sea-floor sediment influence. In much of the ocean, direct human influence and sea-floor influence are most intense along the edge of the continental shelf – an average depth of about 130 m (see Text Box 1.1, Chap. 1), which may occur anywhere from a few kilometers to hundreds of kilometers offshore. About 8% of the world ocean area lies on the shelf (Sverdrup et al. 1942), and most human and sea-floor influences occur within this relatively small area of the ocean. Any conceptual model that describes the land as a homogeneous box connected to a homogeneous ocean misses these important gradients in biotic composition and ecosystem function. Most human activity on Earth

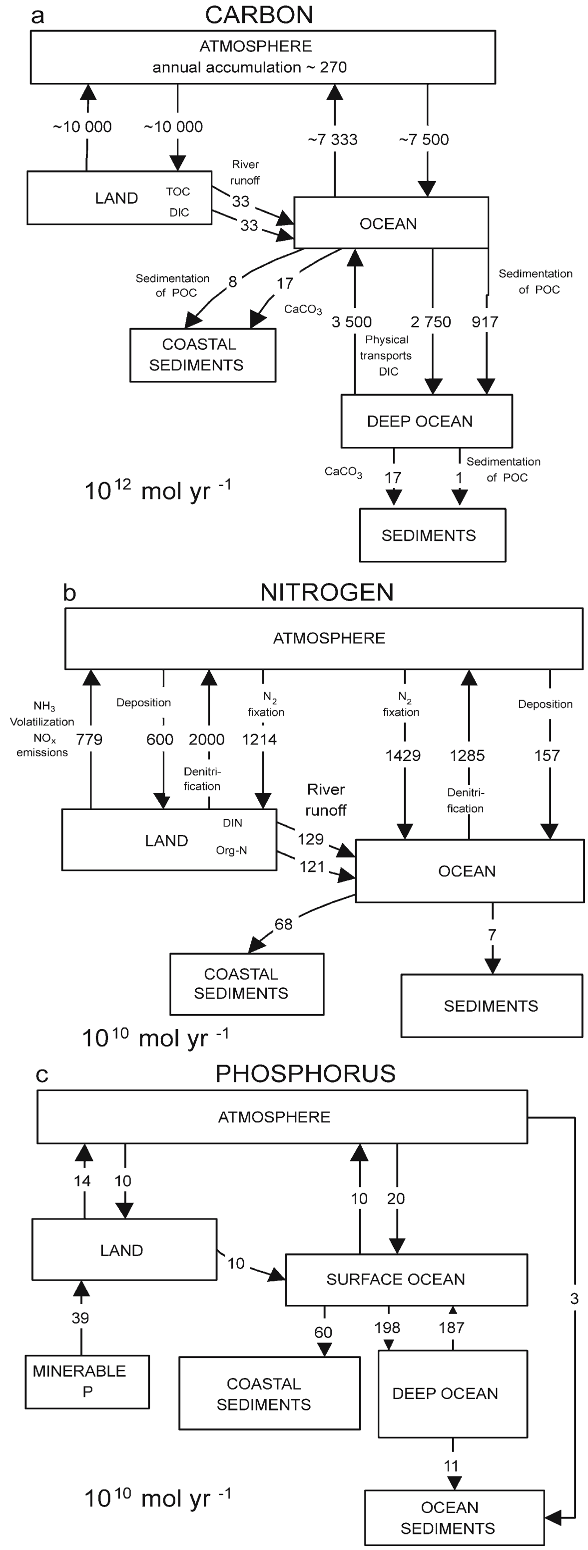


Fig. 3.1. Global budgets. "Conventional wisdom" on global C, N and P cycles. **a** Global carbon cycle, with particular emphasis on the coastal ocean (modified from Prentice et al. 2001). **b** Global nitrogen cycle, with particular emphasis on the coastal ocean (modified from Jaffe 2000). **c** Global phosphorus cycle, with particular emphasis on the coastal ocean (modified from Jahnke 2000)

occurs in this gradient zone between land and sea on both the landward and seaward sides of the coastline.

Standard models of the Earth system deal mostly with vertical fluxes; this has influenced the structure of the IGBP programme and the structure of most global models. In part, this conceptualisation has been driven by the observation that the global carbon budget is dominated by vertical transports (Fig. 3.1a). However, delivery of other materials to the coastal zone and fluxes within the coastal zone are dominated by horizontal transports. This can be recognised from Figs. 3.1b and c if it is assumed that less than 50% of the atmospheric deposition fluxes are likely to occur in the coastal zone.

Flow of both surface runoff and groundwater from land is the dominant source of material delivery from land. A combination of mixing and advection creates bidirectional processes that exchange materials between the coastal zone and the ocean interior. Vertical fluxes of some materials are important. For example, fluxes of gaseous materials (especially CO_2 and O_2) are driven by partial pressure differences between the atmosphere and surface water. The driving mechanisms include both elevation of atmospheric CO_2 due to fossil fuel combustion and internal biogeochemical processes altering local water composition both spatially and temporally. Nitrogen gas also exchanges vertically, largely due to the metabolic processes of nitrogen fixation and denitrification. Fallout of nitrogenous pollutants is also locally important (see Text Box 3.1).

Clearly, the oceanic hydrological cycle includes not only flow from land but also direct precipitation and direct evaporation. It should be emphasised that for C, N and water, the important internal processes regulating fluxes include forward and back reactions that largely cancel one another and, at the scale of the coastal zone, are not important net reactions.

For the vertical fluxes across the air-sea interface, it may be reasonable to treat the whole ocean as a single box; however, the coastal ocean clearly processes organic matter, nutrients and sediments delivered (horizontally, largely by freshwater discharge or runoff) from the land very differently than the open ocean processes the same materials. In effect, the land and coastal ocean are tightly coupled horizontally; the coastal ocean and open ocean are also coupled horizontally. In contrast, the land–open ocean coupling is mainly vertical (via the atmosphere) and is largely restricted to gases and aerosols.

The factors characterising the coastal zone, including its heterogeneity of environments, are the coastal interactions of the marine environment (the composition and rate of the ocean water entering the system), terrestrial inputs (primarily in the form of freshwater inflow and its associated dissolved and suspended loads), and the geomorphology of the coastal system (depth, coastal complexity). Taken together, these factors determine not only the fluxes into the system, but also the residence time of water within the system. If we view the coastal water mass and its associated ecosystems as a biogeochemical reactor, the residence time is a measure of how long the reactions are allowed to proceed, which in turn will strongly affect the relative net rates of conservative and non-conservative reactions (fluxes) within and through the system. Because of the freshwater inputs, estuarine conditions in the coastal zone cover a much broader range of salinities than is common in the open ocean, supporting very different ecosystems and sustaining a wider variety of geochemical as well as biochemical reactions. Some of these issues are discussed in more detail in Sect. 3.2.

3.1.2 Elemental Cycles and Fluxes

Box diagrams illustrating slight modifications of recently published versions of the global C, N, and P cycles are presented as Figs. 3.1a–c. Three characteristics of the three cycles are presented here for consideration:

- First, none of the cycles balances very well. Imbalance in the carbon cycle, which is probably the most intensively studied of the three, is manifested in the so called *missing carbon sink* that has frustrated researchers for more than 20 years (e.g., Schimel 1995, Schindler 1999). The nitrogen cycle is particularly poorly balanced, apparently largely reflecting the problem of deriving confident global estimates of nitrogen fixation and denitrification both on land and in the ocean.
- A second characteristic of the budgets is the contrast of their dominant terms. For example, carbon fluxes are overwhelmingly dominated by atmospheric transfers to and from the land and ocean, while phosphorus fluxes largely represent horizontal (hydrological) transfers. For phosphorus, dust transport can be locally important. Nitrogen, with the aforementioned caveats about uncertainties in nitrogen fixation and denitrification, has strong vertical and horizontal flux components.
- Finally, with sediments being the net repository for land-derived materials that do not accumulate in the atmosphere, most sediments accumulate in the coastal zone. One significance of this observation is that chemical reactions in shallow-water sediment are largely anoxic, in contrast with largely oxic reactions in the water column and the very slow sedimentation regime of the open ocean. The chemical reaction pathways and products differ substantially, so the products of the coastal zone differ markedly from those of the open ocean.

Human activities have greatly perturbed fluxes of some materials to the coastal ocean. Fluxes of both N and P have increased worldwide by more than a factor of two over pre-human estimates (Meybeck 1982, 1998, Howarth et al. 1996, Galloway and Cowling 2002, Smith et al. 2003). Knowledge about nutrient retention and transformations on land and in the coastal zone is, to a large extent, based on studies from the north temperate regions (Billen et al. 1991, Howarth et al. 1996, Jickells 1998, Nedwell et al. 1999, Nixon 1995, Nixon et al. 1996), but knowledge and predictions for tropical regions are increasing (Downing et al. 1999, Seitzinger et al. 2002).

Dramatic changes in the global nitrogen (N) cycle have occurred during the last 100 years due to an increase in easily utilisable N inputs by human activities (Vitousek et al. 1997, Caraco and Cole 1999). It has been estimated that the transfer of riverine reactive nitrogen to the coastal ocean has increased three to four times (Galloway and Cowling 2002, Smith et al. 2003). Human impacts on the global P cycle are less clear, but have apparently more than doubled the inputs to the ocean and caused accumulation of fertiliser P in cultivated soils. This accumulation eventually leads to increased water-borne loads to aquatic ecosystems (Bennett et al. 2001, Smith et al. 2003).

A fourth element, silicon (Si), which has not been a focus of LOICZ studies, warrants attention. Under pristine conditions, Si levels in freshwater tend to be high. Human activities tend to elevate N and P concentrations in water, but do not ordinarily elevate Si concentrations. Instead, elevated N and P in freshwater often cause blooms of siliceous plankton (dominantly diatoms) in lakes, reservoirs and other freshwater bodies. This in turn can lower Si concentrations well below normal concentrations (Turner and Rabalais 1991, Ittekkot et al. 2000). The depletion of Si reaching coastal waters can alter the composition of plankton blooms that occur there, away from typical domination by diatoms to non-diatoms with subsequent alterations to trophic structure (Conley and Malone 1992, Conley et al. 1993, Turner et al. 1998). An alternative to the widely-held view that Fe limits primary production in some oceanic regions replete with N and P (e.g., Coale et al. 1996) is the possibility that low Si concentration limits primary production under these conditions (Dugdale and Wilkerson 1998).

Carbon (C) flux is probably the most complex of the elements which have formed the focus of LOICZ interest to date (Fig. 3.1a). By far the largest flux of C to and from the ocean is via the gas phase (CO_2). This is a bi-directional flux, driven by both biogeochemical reactions within the water and elevated CO_2 in the atmosphere. Under pristine (pre-human impact) conditions, this flux would be slightly negative (Smith and Mackenzie 1987, Sarmiento and Sundquist 1992, Smith and Hollibaugh 1993), due to the net oxidation of organic matter in the ocean and consequent release of CO_2 to the atmosphere. Human activities, largely burning of fossil fuel, have driven this flux rather strongly positive by elevating atmospheric CO_2 partial pressure and causing pressure-driven transfer to the ocean water column. This flux dominates the delivery of C to the ocean. In addition, organic C (about half dissolved, half particulate) is delivered via rivers. While soil erosion has tended to elevate this flux, sediment trapping in the landscape has apparently tended to counter it (Stallard 1998, Smith et al. 2001, 2003). Finally, dissolved inorganic C in river water has probably been elevated somewhat due to enhanced weathering associated with acid precipitation. Of these fluxes, the organic carbon flux, especially the particulate organic carbon flux, is apparently largely retained or processed in the coastal ocean (Smith and Hollibaugh 1993, Berner 1982, Hedges and Keil 1995). Fluxes involving the calcium carbonate minerals (see Fig. 3.1: $CaCO_3$) are numerically small compared with the organic and dissolved inorganic C fluxes, but are disproportionately important as ocean ecosystem indicators and in terms of their significance to low-latitude coastal zone structure and function.

Almost all marine carbonates that are formed in today's ocean are the result of biogenic precipitation in the surface layer. Carbonate contributions to sediments are about equally divided between the oceanic and coastal domains, but this balance appears sensitive to climatic variations (Milliman and Droxler 1996). Noteworthy car-

Text Box 3.1. Nitrogen deposition and the LOICZ nutrient budgets

S.V. Smith and P. Sanhei

Nitrogen deposition should, in principle, be included as a vertical input flux to the nitrogen budgets. Except for a few site budgets for which the authors had estimates of nitrogen deposition, this has not been included in the LOICZ nutrient budgets. In general, this flux is small relative to the horizontal flux terms (horizontal inputs from land; exchanges with the ocean), so this omission should not be a major error. This does not imply that nitrogen deposition is not globally important but rather that, at the scale of individual coastal zone budgets, direct deposition is usually not important. Of course, the horizontal input from land includes nitrogen deposited on, then washed off, the landscape.

When most of the budgets were developed, we did not have a global map of N deposition. We have recently obtained such a map (Fig. TB3.1.1a, from van Drecht et al. 2001). Note the "hot spots" of deposition in the eastern US, much of Europe and much of Asia. Note also that measurable deposition can extend well offshore in some regions. Rather than revising all of the budgets, we have examined the budgets to compare the horizontal loading and vertical deposition of nitrogen. As illustrated in Fig. TB3.1.1b, there is a large range in terrigenous nitrogen load, from < 10 to $> 10^4$ mmol m^{-2} yr^{-1}. The data in Figs. TB3.1.1a and b can be used to calculate atmospheric deposition as a percentage of the LOICZ budgeted load (Fig. TB3.1.1c). Most budget sites with a significant percentage of nitrogen deposition are characterised by very low N load; in these systems non-conservative DIN flux is also relatively low. Our conclusion is that failure to include nitrogen deposition in most of the budgets is not a particular shortcoming.

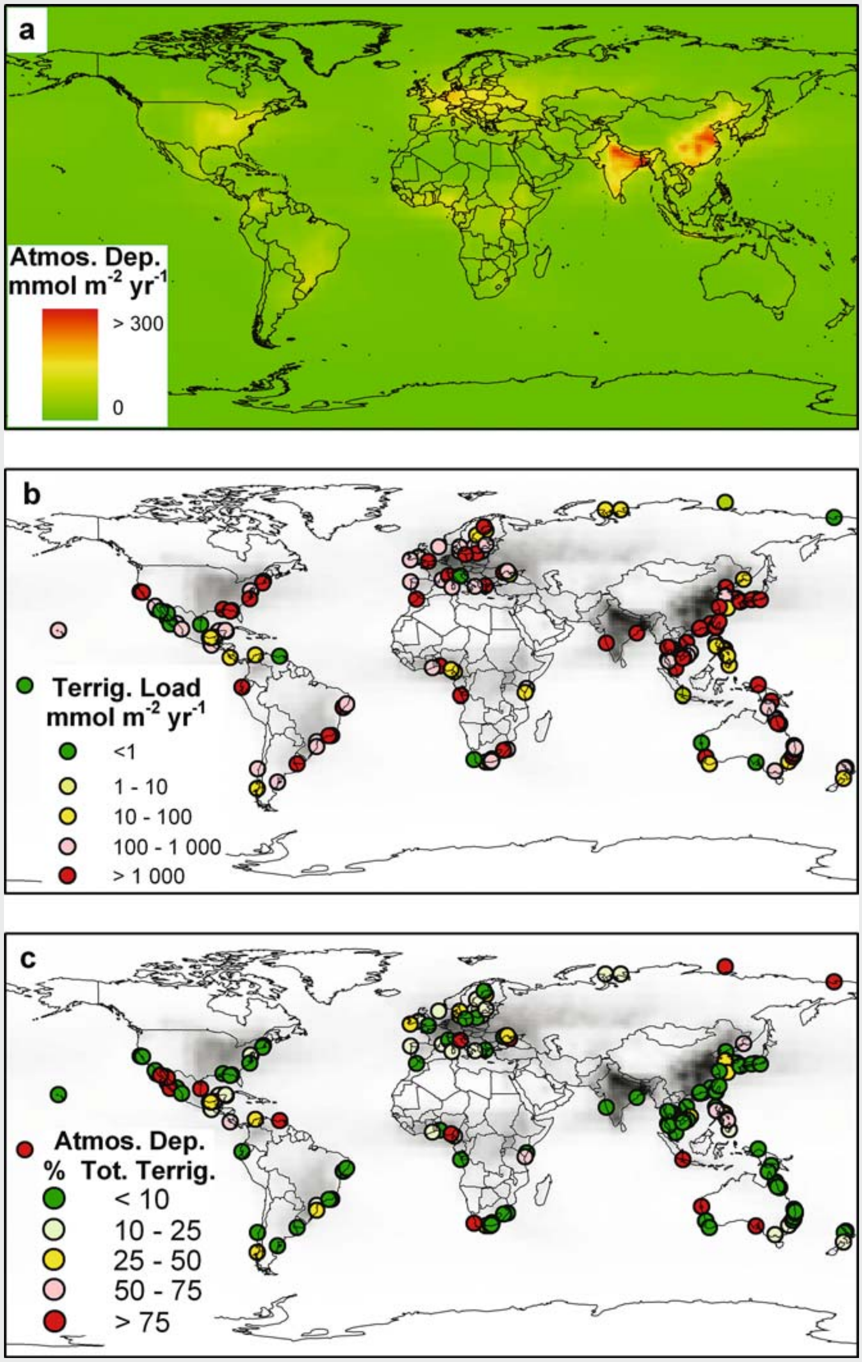


Fig. TB3.1.1.
a Global variation in estimated atmospheric nitrogen deposition (fluxes in mmol $m^{-2}\,yr^{-1}$, from van Drecht et al. 2001).
b Terrigenous nitrogen loading at the budget sites, as estimated during the budgeting and scaled to the area of the sites (fluxes in mmol $m^{-2}\,yr^{-1}$).
c Atmospheric N deposition as a percentage of the budgeted DIN load

bonate producers in shallow tropical waters are the organisms that make up coral reef ecosystems, which are important as habitats, economic resources and biogeomorphic agents and thus determine the physical structure of many coastal environments (Pernetta and Milliman 1995). The exchange of rising atmospheric CO_2 concentrations with the surface ocean shifts the inorganic carbon equilibrium to reduce pH and carbonate ion (CO_3^{2-})

Text Box 3.2. CO_2, calcification and coastal zone issues

R.W. Buddemeier, J.A. Kleypas and S.V. Smith

Intuitively, it would appear that the precipitation of $CaCO_3$ is a sink for atmospheric CO_2. That is not the case. There are various ways that the $CaCO_3$ precipitation reaction can be represented. The following form of the reaction equation demonstrates that the carbon used during the precipitation reaction is derived from bicarbonate (HCO_3^-) in solution, and that the reaction drives CO_2 out of the water.

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \quad (1)$$

As discussed in detail by Smith (1985), Ware et al. (1992), Frankignoulle et al. (1998), Froelich (1988), and Gattuso et al. (1999), the precipitation of $CaCO_3$ truly does release CO_2 to the atmosphere.

In freshwater and as represented by Eq. 1, one mole of CO_2 is released to the atmosphere for each mole of $CaCO_3$ precipitated. The situation is somewhat more complicated for seawater. At the present atmospheric pCO_2 of about 380 µatm and with the buffer capacity of seawater, some of the "CO_2" and "H_2O" produced back-react to HCO_3^- and H^+, so that only about 0.6 moles of CO_2 escapes to the atmosphere for each mole of $CaCO_3$ precipitated.

The chemical behaviour of CO_2 in ocean water is well understood, but it is complex and may seem counterintuitive. In water, dissolved CO_2 forms an equilibrium system described by Eq. 2. The more acid the water, the higher the concentration of CO_2; the more basic, the higher the relative proportion of carbonate ion (CO_3^{2-}), with the bicarbonate ion (HCO_3^-) acting as an intermediate species. Ocean water chemistry is dominated by the bicarbonate ion, with relatively minor amounts of CO_2 and carbonate ion.

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad (2)$$

Increased CO_2 gas in the atmosphere drives more gas into the ocean, across the air-sea interface. Hence, the top 100 or so meters of the ocean has absorbed much of the anthropogenic CO_2. When additional carbon dioxide dissolves in water, it forms H_2CO_3 (carbonic acid), a weak acid that tends to shed a hydrogen ion, which in turn will reduce the concentration of carbonate ion by enhancing the reaction in Eq. 3:

$$H^+ + CO_3^{2-} \leftrightarrow HCO_3^- \quad (3)$$

Carbonate mineral saturation state (Ω) is related to the product of the concentrations of the carbonate and calcium ions. If the water is in thermodynamic equilibrium with the solid phase (i.e., neither dissolution nor precipitation tends to occur), then $\Omega = 1$. Most surface ocean waters are supersaturated with respect to calcium carbonate minerals ($\Omega > 1$). The tropical waters where coral reefs occur have commonly had $\Omega > 4$ for the past several million years.

Figure TB3.2.1 illustrates the calculated changes occurring as a result of rising atmospheric CO_2 levels. By the time atmospheric CO_2 doubles later in this century (as projected by the International Panel on Climate Change 2000), oceanic carbonate ion concentrations will be about two-thirds of their pre-industrial value. Figure TB3.2.2 illustrates with maps the effects of rising atmospheric CO_2 on carbonate (aragonite) saturation state over two centuries of human influence.

Many calcifying organisms in the ocean depend on the carbonate ion concentration in water to build their skeletons. When its concentration is reduced, calcification rates reduce, resulting in either smaller or structurally weaker organisms, or both, with resultant effects on structure of coastal habitat. The calcification effects of changing CO_2 levels have been experimentally documented for corals and coralline algae (reviewed by Gattuso et al. 1999, Marubini et al. 2003), ecosystems (Langdon et al. 2000), coccolithophores (Riebesell et al. 2000) and foraminiferans (Barker and Elderfield 2002).

Some of the ecological implications for coral reef systems have been described by Kleypas et al. (2001). The potential alteration or loss of reef communities has implications ranging from biodiversity to fisheries and tourism. The structural degradation of reefs has the potential to affect coastal protection (and hence habitability of coasts and especially of small islands) and the geomorphic controls on water circulation and residence times – major factors in coastal zone biogeochemistry.

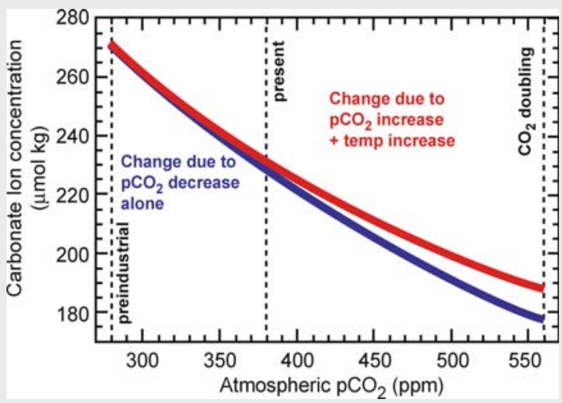


Fig. TB3.2.1. Changes in carbonate ion concentration in typical tropical surface ocean water in response to changes in atmospheric CO_2 concentrations

concentration. This has been shown to decrease the calcification rates of corals, coralline algae and other organisms (Kleypas et al. 1999, see also Text Box 3.2). CO_2 emissions over the past and coming centuries are likely to have significant effects on ecosystems dependent on calcifying organisms. In the coastal zone, changes in these ecosystems may influence both the natural system dynamics and the activities of humans in ways that result in large second-order changes in sedimentary and organic carbon fluxes. Originally identified as important issues for consideration by LOICZ, these aspects of both carbon fluxes and the biological and environmental implications of changes in the coastal carbonate carbon sinks are among the important topics remaining to be addressed.

3.2 Estimates of C, N and P Fluxes in the Coastal Zone

The LOICZ objectives focus on understanding the role and contributions of the coastal zone in the global cycles. Such an understanding requires measurement or modelling of the cumulative effects of system-level fluxes over the entire globe – a daunting task, given the dimensions, heterogeneity and general lack of information about the biogeochemistry of the approximately 1 million km-long world coastline (see Text Box 1.8, Chap. 1). We have approached this as a problem of upscaling the local and regional measurements or estimates of flux to the global scale.

◀

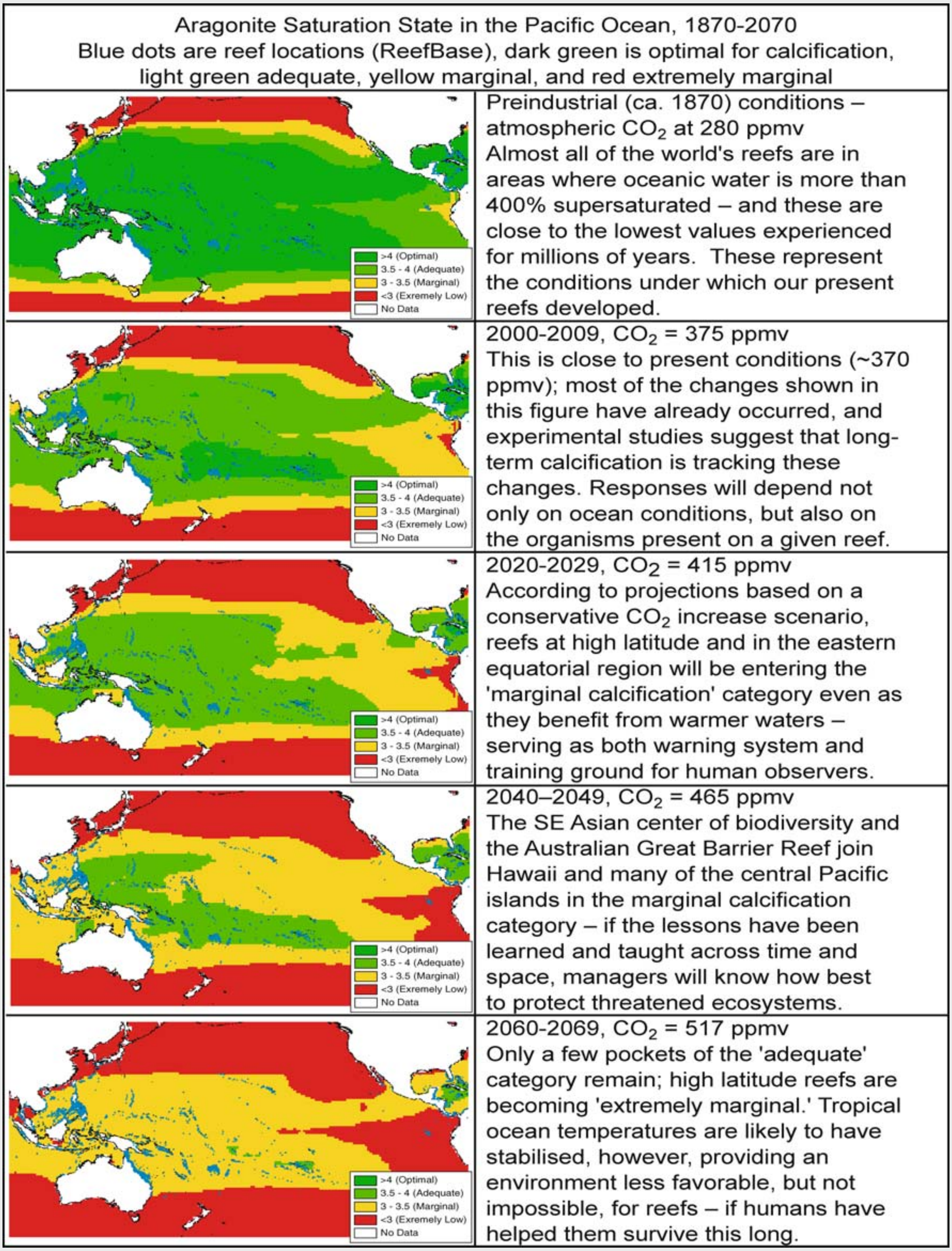


Fig. TB3.2.2. Mapping the effects of rising atmospheric CO_2 on carbonate (aragonite) saturation state over two centuries of human influence (Guinotte et al. 2003)

Text Box 3.3. Key Abbreviations – LOICZ Nutrient Budgets (see Gordon et al. 1996)

Nutrients and nutrient flux:

- DIC Dissolved inorganic carbon
- DOC Dissolved organic carbon
- DIN Dissolved inorganic nitrogen
- DON Dissolved organic nitrogen
- DIP Dissolved inorganic phosphorus
- DOP Dissolved organic phosphorus
- ΔDIN net flux (non-conservative) flux of DIN for the budgeted system
- ΔDIP net flux (non-conservative flux) of DIP for the budgeted system

System performance:

- p Primary production (of the system)
- r Respiration (of the system)
- $[p - r]$ Net ecosystem metabolism (NEM) or net ecosystem production (NEP)
- [denit] Denitrification
- [nfix] Nitrogen fixation
- [nfix – denit] Net nitrogen metabolism (of the system)

System physics:

- V_Q Volume of river flux, runoff, or non-point sources from the local drainage basin
- V_G Volume of groundwater
- V_R Residual flow of the system
- V_X Mixing volume of the system
- S_{SYS} Salinity of budget system
- S_{OCN} Salinity of ocean adjacent to budget system
- S_G Salinity of ground water
- τ Water residence time of the system

Text Box 3.4. The algebra of the LOICZ methodology

D. P. Swaney and S. V. Smith

One-compartment, well-mixed system

Water and salt budgets

For a simple one-compartment estuarine system (Fig. 3.4.1), the change in mass of water (V) and salt (S) over some representative period (e.g., one year) is equal to the sum of the average water or salt fluxes into and out of the system during the period:

$$\Delta V = \overline{V_Q} + \overline{V_O} + \overline{V_G} + \overline{V_P} + \overline{V_E} + \overline{V_R} \qquad (1)$$

$$\Delta VS_{SYS} = \overline{V_Q S_Q} + \overline{V_O S_O} + \overline{V_G S_G} + \overline{V_R S_R} + \overline{V_X}(S_{OCN} - S_{SYS}) \qquad (2)$$

Following LOICZ convention, inflows to the system are taken to be positive and outflows negative. Subscripts refer to:

- Q river flux, runoff, or non-point sources from the local drainage basin,
- O point sources directly discharging into the system,
- G groundwater sources,
- P direct precipitation onto the system,
- E evaporation from the system (negative in sign),
- R residual freshwater flow between the system and the adjacent open sea (negative for "positive" estuaries, positive for negative estuaries),

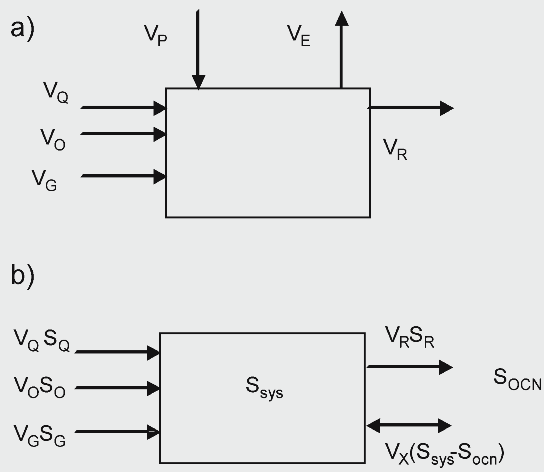


Fig. TB3.4.1. Schematic of (**a**) freshwater fluxes in a single-box model and (**b**) corresponding salinity fluxes, from which the V_X term can be calculated

3.2.1 Current Information Availability

The international LOICZ synthesis of global nutrient flux information has not been a field-based research effort, even though field studies have been stimulated and subsequently undertaken within the context of the project. Rather, the program has been a concerted, globally-directed effort to locate and use existing (or secondary) data. This has been done through literature searches, web posting of ongoing efforts, development of analytical tools and holding workshops designed to enlist the collaboration of the wider scientific community in the contribution of biogeochemical budget information in an internally consistent framework of data analysis (see Chap. 1, Sect. 1.5).

3.2.1.1 *LOICZ Budget Calculation Methodology*

The LOICZ methodology uses a few fundamental assumptions, including that of mass balance, to infer estimates of the community metabolism of coastal systems. The inputs to and the calculated results of these estimates provide the flux estimates. The general approach is discussed at *http://data.ecology.su.se/mnode/methods.htm*, and evolved from an earlier LOICZ publication (Gordon et al. 1996). The approach begins with construction of a simple, steady-state mass balance of water and salt. Together, these quantify the flows of freshwater and seawater that passively transport nutrients from terrestrial, atmospheric and oceanic sources. The products of these flows and mean dissolved concentrations of each of these sources constitute the nutrient fluxes necessary to construct steady-state nutrient mass balances for the system. In the absence of internal sources or sinks, these nutrient inflows and outflows should balance (conserva-

◀

- X exchange flow between the system and the adjacent open sea (positive by definition),
- OCN average value for the adjacent local ocean,
- SYS average value for the system.

Note that if flow-weighted average salinities are assumed, Eq. 2 can be written:

$$\Delta V S_{SYS} = \overline{V_Q}\,\overline{S_Q} + \overline{V_O}\,\overline{S_O} + \overline{V_G}\,\overline{S_G} + \overline{V_R}\,\overline{S_R} + \overline{V_X}\,\overline{S_{OCN} - S_{SYS}} \tag{3}$$

At steady-state the left-hand sides of Eqs. 1 and 2 are zero, and they can be rearranged to solve for V_R (system residual flow) and V_X (system mixing volume):

$$\overline{V_R} = -\left(\overline{V_Q} + \overline{V_O} + \overline{V_G} + \overline{V_P} + \overline{V_E}\right) \tag{4}$$

$$\overline{V_X} = \frac{\overline{V_Q}\,\overline{S_Q} + \overline{V_O}\,\overline{S_O} + \overline{V_G}\,\overline{S_G} + \overline{V_R}\,\overline{S_R}}{\overline{S_{SYS} - S_{OCN}}} \tag{5}$$

In most cases, V_X reduces to:

$$\overline{V_X} = \frac{\overline{V_R}\,\overline{S_R}}{\overline{S_{SYS} - S_{OCN}}} \tag{6}$$

Henceforth, we drop the overbars, remembering that the flux terms are average values over the period of interest. Note that the residence time of water in the system can be written:

$$\tau = \frac{V}{V_X + |V_R|}$$

which is always shorter than the freshwater fill-time,

$$\tau_f = \frac{V}{|V_R|}$$

Nutrient budgets
A mass balance for nutrients in a one-compartment system, assuming a fixed system volume, flow-weighted average nutrient concentrations, $Y_i(t)$ and internal sources or sinks ΔY is:

$$V(Y_{SYSF} - Y_{SYSI}) = V_Q Y_Q + V_O Y_O + V_G Y_G + V_P Y_P + V_R Y_R + V_X (Y_{OCN} - Y_{SYS}) + \Delta Y \tag{7}$$

where the subscripts indicate the fluxes corresponding to those for water and salt, and where F and I denote final and initial concentrations, respectively. Under the assumption of steady-state, this can be rearranged to solve for the internal source/sink term, ΔY:

$$\Delta Y = + V_X Y_{SYS} - V_R Y_R - V_Q Y_Q - V_O Y_O - V_G Y_G - V_P Y_P - V_X Y_{OCN} \tag{8}$$

For phosphorus (ΔDIP), the source/sink term is interpreted as the amount of phosphorus uptake or release associated with net ecosystem production. For nitrogen (ΔDIN), the source or sink is attributable to both NEM and the net effect of nitrogen fixation and denitrification.

Stratified systems

Water and salt budgets
For a simple stratified system with estuarine flow, two layers must be considered, along with their characteristic flows (Fig. 3.4.2). In classic estuarine circulation, water flows from the upper layer to the sea (V_{Surf}) and from the sea (at depth) into the lower layer (V_{Deep}), with an advective flux from the lower to upper layer equal to the inflow, which maintains mass balance of water. A vertical mixing flux (V_z) maintains salinity balance. As a result, at steady state, both V_{Deep} and V_z can be estimated from the salinity structure and the residual flow of the system:

Water balance, surface layer:

$$V_{Surf} = -(V_Q + V_O + V_G + V_P + V_E + V_{Deep}) \tag{9}$$

Salt balance, surface layer

$$0 = V_{Surf} S_{Surf} + V_{Deep} S_{Deep} + V_Z (S_{Deep} - S_{Surf}) \tag{10}$$

Salt balance, deep layer

$$0 = V_{Deep} S_{Deep\_Ocean} - V_{Deep} S_{Deep} - V_Z (S_{Deep} - S_{Surf}) \tag{11}$$

Thus:

$$V_Z = \frac{V_{Deep}(S_{Deep\_Ocean} - S_{Deep})}{S_{Deep} - S_{Surf}} \tag{12}$$

$$V_{Deep} = \frac{V_R S_{Surf}}{S_{Surf} - S_{Deep\_Ocean}} \tag{13}$$

Nutrient budgets
For more complex systems, because concentrations within the system are not homogeneous, the nutrient budget calculations must be performed for each box and layer. For example, for the surface layer of a one-compartment stratified system, the ΔDIP value for the surface layer is given by:

$$\Delta DIP_{surf} = + V_Z(\mathrm{DIP}_{surf} - \mathrm{DIP}_{Deep}) - V_{Deep}\mathrm{DIP}_{Deep} - V_{surf}\mathrm{DIP}_{surf} - V_Q \mathrm{DIP}_Q - V_O \mathrm{DIP}_O - V_P \mathrm{DIP}_P - V_G \mathrm{DIP}_G \tag{14}$$

and for the deep layer by:

$$\Delta \mathrm{DIP}_{deep} = V_{Deep}(\mathrm{DIP}_{Deep} - \mathrm{DIP}_{Deep\_Ocean}) - V_Z(\mathrm{DIP}_{surf} - \mathrm{DIP}_{Deep}) \tag{15}$$

assuming that all terrestrial and atmospheric sources flow directly to the surface layer.

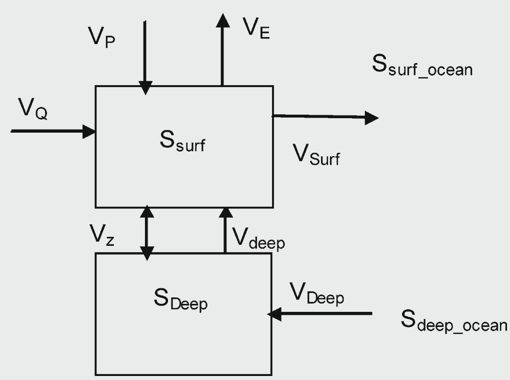


Fig. TB3.4.2. Two-layer box model showing water and salinity fluxes for a stratified system with estuarine circulation

tion of mass). Departures from this balance indicate the presence of a net source or sink (i.e., non-conservative flux). Non-conservative fluxes of DIP are attributed to net ecosystem metabolism (NEM or $[p - r]$), in the absence of evidence of other competing processes. Non-conservative fluxes of DIN are attributed to the net balance of nitrogen fixation minus denitrification [nfix – denit] within the system, after accounting for the flux of nitrogen associated with NEM. Text Box 3.3 refers to key abbreviations applied within the LOICZ nutrient budgeting process; Text Box 3.4 reviews these calculations for a one-compartment system, and briefly discusses the extension to multi-compartment systems.

The budgets provide estimates of non-conservative fluxes for DIP and DIN (and, potentially, other materials), with the estimates being constrained only by data quality and ecosystem suitability for budgeting. Stoichiometric relationships are assumed between P, N and C. These relationships provide insight into the net biogeochemical reactions that are occurring, with the quality of that insight reflecting how well the ecosystem function matches those assumed stoichiometric assumptions.

Text Box 3.5. Why not estimate carbon flux directly?

S. V. Smith

A major question within LOICZ has been to determine the degree to which the coastal zone produces or consumes organic carbon, yet LOICZ budgeting has been directed at estimating phosphorus and nitrogen fluxes, and not carbon. Why? There are two answers to this question.

In the first place, nutrient data for both river inflows and the marine environment are far more widely available than carbon data. Restricting budgets to sites with carbon data would greatly reduce the number of possible budgets. Inasmuch as the desire was to use a near-uniform budgeting approach, the comparisons were restricted to the phosphorus-based estimates of $[p - r]$ While there are a few individual budget sites globally with direct carbon budgets, these few sites have not been used in the comparisons here.

The second issue is analytical quality of data, relative to data demand. This is best explained by example. The dissolved inorganic carbon (DIC) content of seawater is close to 2 mmol l^{-1}, and good analytical precision of DIC measurements is about 0.01 mmol l^{-1}. While higher precision can be achieved, data at even this resolution are rare in coastal datasets. Nutrient concentrations in surface seawater are proportionally far more variable than DIC, but DIP and DIN concentrations are typically of the order of 0.001 mmol l^{-1} (1 µmol l^{-1}), with typical precision of better than 0.00005 mmol l^{-1}.

A change in DIP of 0.0001 mmol l^{-1} could be readily measured. This change due to uptake of DIP into organic matter would lead to a DIC uptake of about 0.01 mmol l^{-1} – below the level of analytical resolution for most available coastal data. While this is only an example, it makes the point that changes in DIP concentrations due to organic reactions are generally more readily resolved than changes in DIC.

3.2.1.2 *The LOICZ Research Strategy*

3.2.1.2.1 *Choice of Sites and Consideration of Data*

Budgets have been developed in several ways: (*a*) in collaborative workshops that brought regional scientists together with the express purpose of organising previously-collected data along LOICZ budget guidelines (Gordon et al. 1996), (*b*) as "contributed budgets" from researchers working independently and using the budget guidelines, and (*c*) from studies of coastal systems obtained from the literature, from which the data could be reworked to conform to LOICZ budget guidelines.

Effectively, three criteria have been used to determine sites for which a biogeochemical budget can be developed:

- Is there a reasonable expectation of getting the data required to construct a budget?
- Is there a contact person for the site with access to the required data (i.e., a researcher with the interest and means of constructing a budget)?
- Does the budget help obtain general, worldwide coverage?

3.2.1.2.2 *Choice of Variables*

It is easily argued that estimations of fluxes of dissolved inorganic carbon, particularly non-conservative fluxes, are better made using the stoichiometrically-linked variables DIN and DIP. The relatively large amount of DIC in the coastal zone, compared with DIN and DIP, suggests that the DIC pool is relatively insensitive to effects of ecosystem metabolism, and thus the inverse problem of estimating metabolism from measured concentrations and their associated fluxes is much better addressed using DIP. Consequently, unless special care has been taken in the sampling and analysis of DIC, LOICZ budgets use DIP and Redfield stoichiometry to estimate NEM (see Text Box 3.5).

Variables required to construct mass balances are steady-state values of fluxes of water, salt and nutrients, or equivalently, long-term averages of water fluxes and associated area- or flux-weighted concentrations (to calculate nutrient fluxes). Table 3.1 contains a list of required variables for a typical one-compartment, one-layer budget.

3.2.1.2.3 *System Complexity and Data Issues*

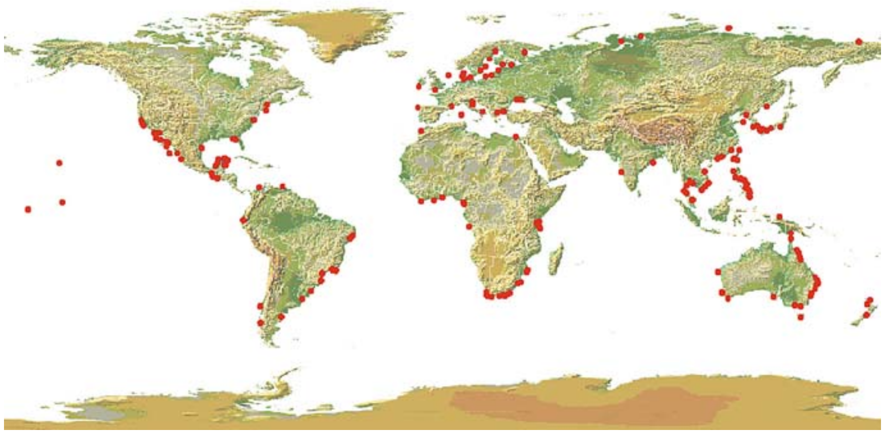
Spatial complexity. System complexity, here considered to be any characteristic of a system that requires description beyond steady, homogeneous, single compartments, can complicate data requirements(Webster et al. 2000). Stratified estuaries require estimates of concentrations in both layers, and care is required in defining the boundary between layers. Spatially non-homogeneous systems, such as those of variable depth, extended longitudinal gradients, or containing significant sub-basins or tribu-

Table 3.1.
Data required for and derived from a one-compartment one-layer LOICZ budget

Required variables
Physical characterisation of the system: mean depth, surface area, volume
Water budget: annual runoff (V_Q), annual point source flow (V_O), annual groundwater flow (V_G), annual direct precipitation (V_P), annual evaporation from the system (V_E)
Salt budget[a]: S_Q, S_O, S_O, S_P, S_{sys}, S_{ocn}
DIP budget[a]: DIP_Q, DIP_O, DIP_G, DIP_P, DIP_{sys}, DIP_{ocn}
DIN budget[a]: DIN_Q, DIN_O, DIN_G, DIN_P, DIN_{sys}, DIN_{ocn}
Derived variables
Estuarine mixing volume, V_X
Estuarine water residence time, τ
"Non-conservative fluxes", ΔDIP, ΔDIN
Net ecosystem metabolism (NEM) = primary production minus respiration, [$p - r$]
Net nitrogen fixation minus denitrification, [nfix – denit]

[a] Salinity, DIN and DIP concentrations are assumed to represent an appropriate flux-average, system average or oceanic average as necessary.

Fig. 3.2.
Budget sites. Global distribution (April 2002)



taries, sometimes require treatment as multiple compartments, each of which requires concentration data and flux estimates. Often, boundaries between these compartments are clearly suggested by system geometry.

Temporal complexity. Seasonally-varying systems can be treated as conventional systems, if data sufficient for constructing seasonally flow-weighted average concentrations are available. Otherwise, it may be more meaningful to construct budgets for single seasons, noting that dramatically different behaviour may be manifested in, for example, the dry season compared with the wet season of monsoonal coastal systems. Finally, while we acknowledge the significance of episodic loads and flushing in some systems (e.g., Furnas 2003), these events remain largely beyond the scope of the LOICZ approach due to limitation of data.

Operationally, our approach assumes that non-conservative fluxes during short-term, high-flow episodes are the same as these fluxes during the longer, low-flow periods. Two rationales for this assumption can be offered. First, high-flow events are likely to be so dominated by hydrographic fluxes that any non-conservative flux would be difficult to detect. Second, as long as these periods are short and infrequent, quantitatively large deviations from the assumption of "normal" non-conservative fluxes would be needed to seriously bias the estimated average fluxes.

3.2.1.2.4 *Additional System Information*

Other information, while not required for the data analysis, is helpful. If primary production for the system is available, then net ecosystem metabolism (NEM) can be compared with gross system metabolism. Similarly, benthic nutrient fluxes (usually releases) can be compared with the magnitude of NEM. If individual measurements of denitrification or nitrogen fixation are available, these can be compared with the estimate of [nfix – denit]. Many characteristics of the associated catchment basin may be relevant in understanding the controls and changes on system metabolism (e.g., population density, land use, economic development, physiography).

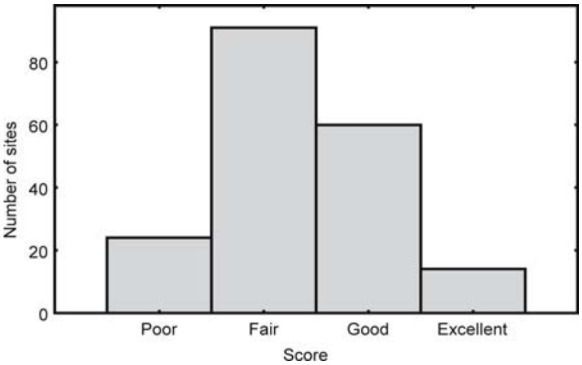


Fig. 3.3. Budget Sites. Frequency distribution of *ad hoc* quality assessment (relative score: 0=poor; 1 = fair; 2 = good; 3 = excellent)

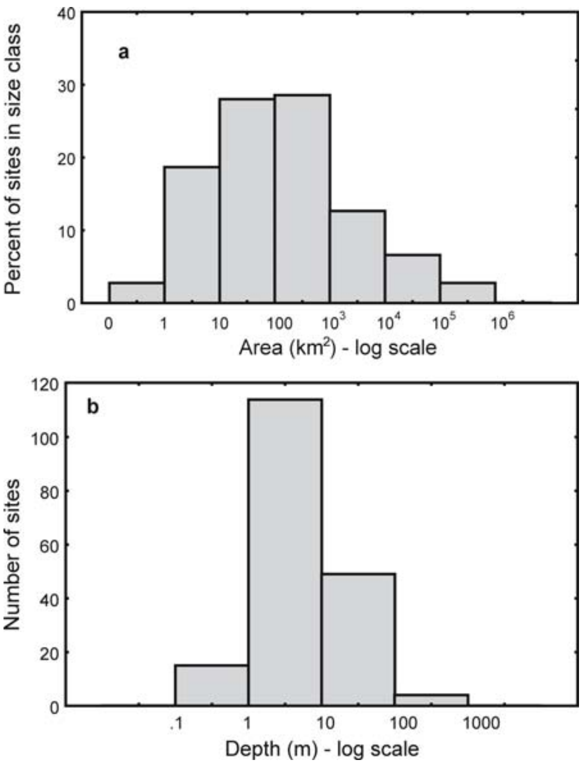


Fig. 3.4. Budget sites. Frequency distribution of (**a**) system area and (**b**) average depth

Text Box 3.6. Expert judgment of budget quality

S.V. Smith

How good are the individual budgets? From the beginning of the LOICZ project, it was clear that some evaluation of budget quality was needed. Of course, formal statistical techniques exist for considering analytical variability for each dataset and both spatial and temporal environmental variability. The most desirable situation would have been to be able to apply such a formal statistical analysis. Unfortunately, for most of the sites the data are not available to undertake such a formal analysis. Thought was given to making "expert judgments" of both the analytical and environmental variability for each site, and then undertaking a formal analysis. In the end, it was decided that the whole evaluation of budget quality was probably best done with expert judgment.

Criteria that went into this judgment included:

- the amount of data available, both in terms of spatial distribution of data representative at a single time and how representative the data seemed to be of temporal variation;
- the likely environmental quality of the data; and
- how the results measure up in terms of the guidelines (see Text Box 3.7).

Finally, systems with residence times near or below 1 day were not considered reliable, on the basis that they had insufficient time to develop a net non-conservative signal. The scores assigned were as follows:

0. Budget was not considered to be reliable (i.e., poor).
1. Budget was considered marginally reliable, but without any basis for total dismissal (i.e., fair).
2. Budget was probably satisfactory but may not have captured temporal variation effectively (i.e., good).
3. Budget appeared highly reliable (i.e., excellent).

3.2.2 Fluxes and Variability of Fluxes

3.2.2.1 *Global Distribution of Budget Information*

Collection of budget information is ongoing. Approximately 200 sites had been budgeted as of April 2002 (Fig. 3.2), the cut-off date for information used in this assessment. Of these sites, 75–85% are regarded as reliable enough for consideration in statistical analyses of a budget dataset (Fig. 3.3, Text Box 3.6). The dataset can be characterised simply in terms of frequency distributions of its various collected or derived variables.

While the coastal zone is generally considered as a relatively narrow ribbon extending to ~200 m depth (e.g., Pernetta and Milliman 1995), there is considerable variation in the area and depth of individual coastal ecosystems within the zone. System area of the sites that have been budgeted during the LOICZ project (Fig. 3.4a) is distributed approximately log-normally (i.e., normally distributed on a log scale) over 7 orders of magnitude, ranging from the 0.5 km^2 Lough Hyne, Ireland, to the 900 000 km^2 East China Sea. Average system depth (Fig. 3.4b) is also distributed approximately log-normally over ~3 orders of magnitude, from ~0.4 m in S'Ena Arrubia, Italy to > 500 m in Sogod Bay, Philippines. Relatively small coastal features such as fjords and trenches may have great depth, while shelf seas typically are < 100 m.

System salinity represents the salinity of the individual budget sites and oceanic salinity is the salinity immediately seaward of the sites. Both system and oceanic salinity distributions (Fig. 3.5a) are uni-modal but strongly skewed. The mode of salinity appears to be close to that of typical open-ocean seawater (~35 psu), with some higher salinities largely reflecting systems in which evaporation exceeds precipitation. The low-salinity tail of the frequency distribution includes many systems (e.g., the Baltic Sea and its subsystems) in which the "oceanic"

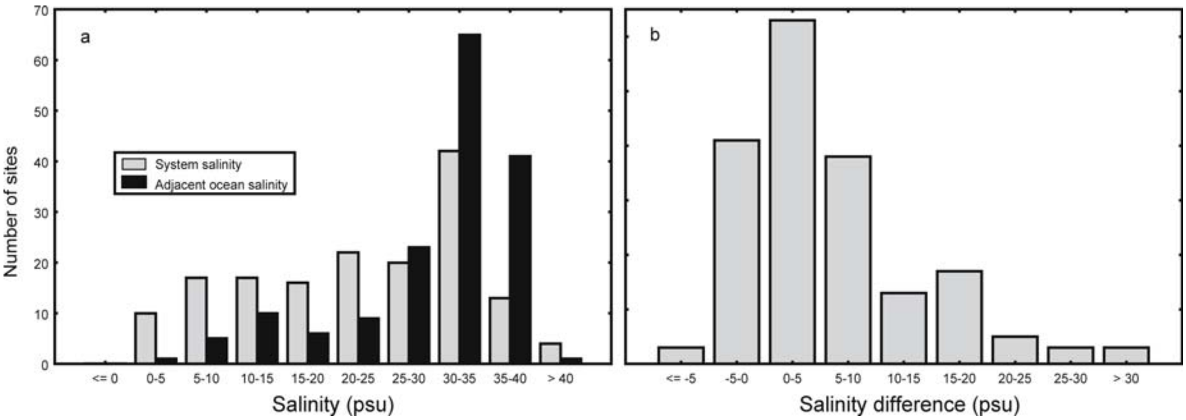


Fig. 3.5. Budget sites. Frequency distribution of (**a**) system and local oceanic salinities and (**b**) oceanic-system salinities

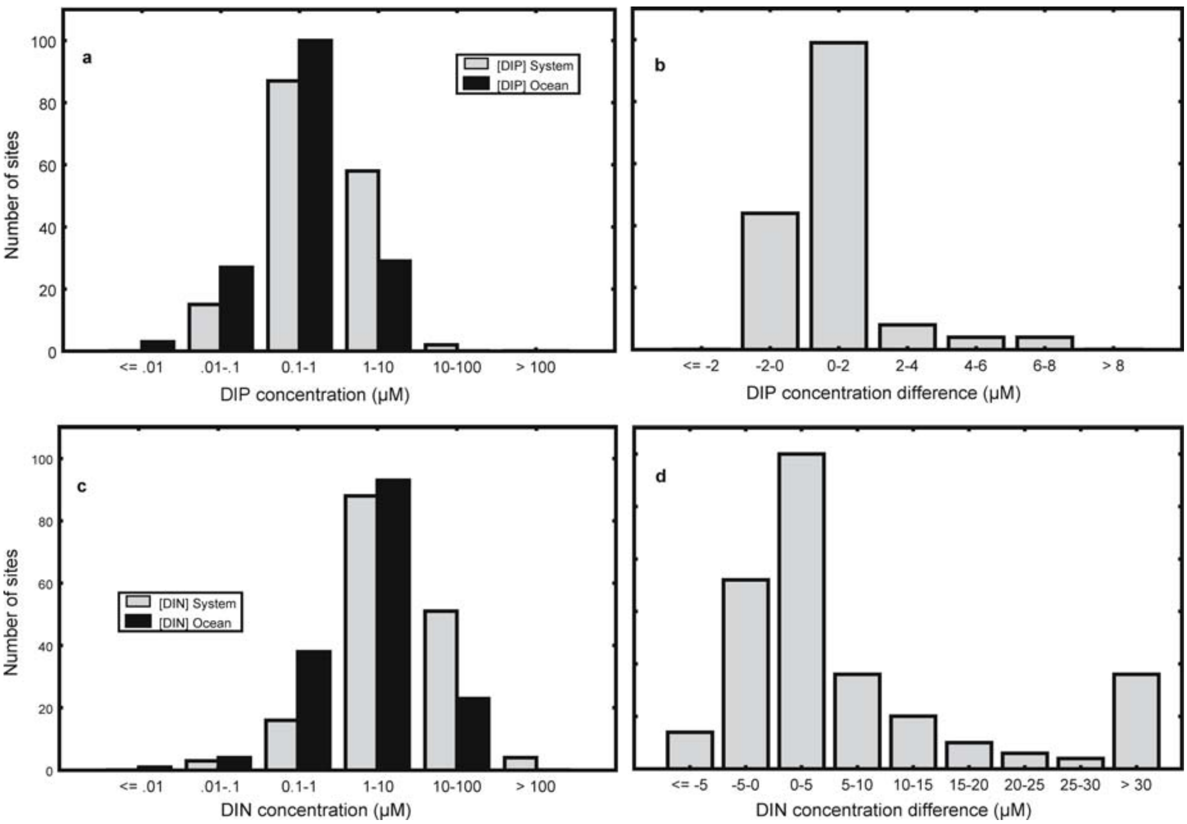


Fig. 3.6. Budget sites. Frequency distribution of (**a**) system and local oceanic DIP concentrations, (**b**) system-ocean DIP differences, (**c**) system and local oceanic DIN concentrations and (**d**) system-ocean DIN differences

source is not full strength seawater. Salinity difference between the local ocean end-member and the system provides a measure of the degree of freshwater dilution within the system. The distribution of ocean minus system salinity differences (used to calculate V_X) (Fig. 3.5b) is also skewed. Most systems exhibit relatively low gradients (between 0 and 5 psu); some are negative, reflecting hypersaline lagoons, while the remainder span the full range between 0 and 35 psu. The maximum values reflect the full seawater minus freshwater extreme.

The distributions of DIP and DIN concentrations are also skewed on a linear scale, but as for area and depth, they reveal an approximately log-normal distribution (Fig. 3.6a and c). The corresponding system-ocean nutrient concentration gradients are skewed in the opposite direction from salinity gradients, reflecting the dominance of terrestrial over oceanic dissolved nutrient sources (Fig. 3.6b and d). This seems especially pronounced in the case of DIN distribution, which shows a secondary node at the positive end of the system-ocean gradient.

3.2.2.2 *Water Fluxes*

The volume of water passing through the budgeted systems spans 6 orders of magnitude, and the distribution of these flows is approximately log-normal. Freshwater flows (V_Q) to the systems from riverine sources and other terrestrial runoff (Fig. 3.7a) span from $< 10^{-3}$ km^3 yr^{-1} to $> 10^3$ km^3 yr^{-1}. Residual flow (V_R) between these systems and the ocean (generally negative, indicating outflows) spans a similar range (Fig. 3.7b), although a secondary mode of positive residual flows occurs for negative estuaries as seawater intrudes to replace net evaporation. The distribution of exchange flow (V_X) between these systems and the ocean spans a slightly greater range than V_Q (Fig. 3.7c).

3.2.2.3 *Loads and Exchanges of DIP and DIN*

The distribution of terrestrial + atmospheric DIP and DIN loads to the systems (Fig. 3.8) is also approximately log-normal, but with a secondary mode at the low end of the distribution corresponding to that observed in the distribution of V_Q. Note that atmospheric load is usually small compared with terrestrial load, but that exceptions exist, notably for systems of large areal extent relative to their catchment size (see Text Box 3.1). Fluxes of DIP and DIN associated with V_R also have two modes in their distributions, but in this case they correspond to net fluxes to and from the system. The dominant (negative) mode reflects the usual transport of system nutrients to the sea. The positive mode (inward) corresponds to the positive mode of V_X associated with negative estuaries. The bimodal distribution of the nutrient transport associated with V_X is solely due to the bimodal nature of this flow. Nutrient concentrations in the system greater than those of the ocean result in a negative nutrient flux (outflow) associated with V_X, and a nutrient concentration "deficit" results in an inward nutrient flux.

3.2.2.4 *Other Information Derived from the Budgets*

A key variable derived from basic morphometry and water budget analysis is the estimate of system water exchange time (see Sect. 3.2.1.1 and Text Box 3.4). This variable has obvious significance in the interpretation of nutrient dynamics. Its distribution over the budgeted sites (Fig. 3.9) reflects the log-normal distribution of volume and water flows.

Finally, the question of budget quality has been addressed simply by *ad hoc*, expert assessment (Text Box 3.6), and is partially based on guidelines for budget quality (Text Box 3.7). Each budget is assigned a quality rating (0–3) based on review of the data used to develop it and the plausibility of the magnitudes of its resulting fluxes. While most of the budgets receive a rating of fair or better, a significant fraction of the 200 site budgets are not regarded as useful from the standpoint of developing reliable statistics on fluxes and metabolic performance of the systems (Fig. 3.3).

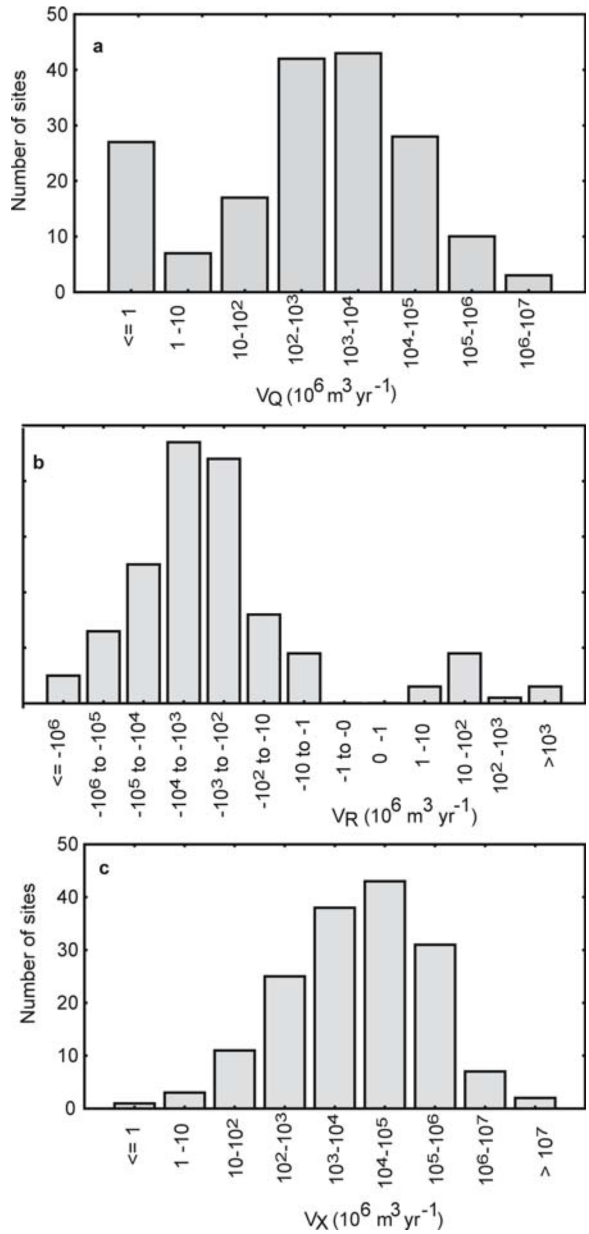


Fig. 3.7. Budget sites. Frequency distribution of (**a**) freshwater riverine, V_Q and runoff flows, (**b**) residual flows, V_R (note: negative sign represents an outflow, positive sign represents an inflow; positive and negative flows on the histogram are binned in log increments) and (**c**) exchange flows, V_X (positive by definition; in stratified systems this is V_D)

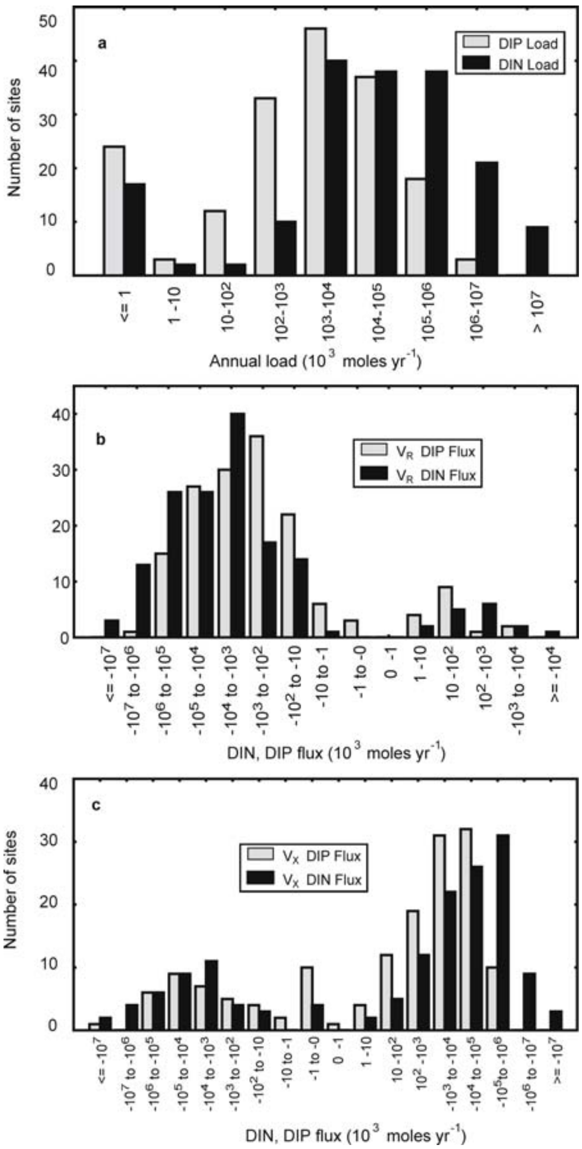


Fig. 3.8. Budget sites. Frequency distribution of (**a**) terrestrial + atmospheric DIN and DIP loads, (**b**) DIN and DIP fluxes associated with residual flows (see note for Fig. 3.7b regarding scale) and (**c**) DIN and DIP fluxes associated with exchange flows (see note for Fig. 3.7c regarding scale)

3.2.3 Non-conservative Fluxes: Their Distributions, Relationships to Other Variables and Biogeochemical Interpretation

The data gathered for the nutrient budget dataset described above include the terrestrial/atmospheric loadings, advective water flow and mixing, and permit the estimation of associated nutrient fluxes. Under the assumption of steady-state, they additionally permit estimation of the terms that describe internal uptake or release of these dissolved nutrients. In the jargon of oceanography, these internal uptake and release fluxes are indicative of non-conservative fluxes. In principle, the LOICZ budgeting procedure does not require the assumption of steady-state (Gordon et al. 1996). In practice, most datasets used during LOICZ were too sparse to be used in any manner other than with this assumption. Apparent non-conservative fluxes arise because reacting materials have sources or sinks other than advection, mixing and dilution or concentration via freshwater gains or losses. Hence, these reactive materials are not conserved relative to water and salt. Note that the calculations of these fluxes give the *net* values, and that these net fluxes are those most relevant to the role of any Earth system compartment relative to its neighbours.

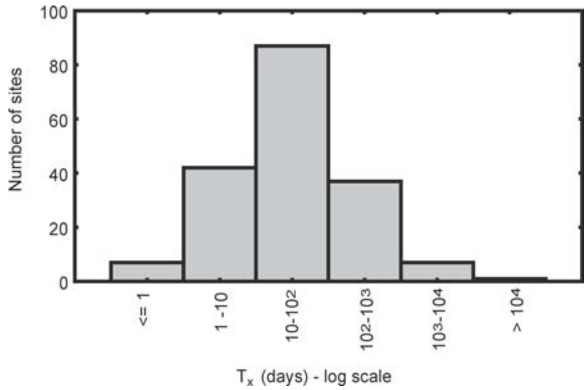


Fig. 3.9. Budget sites. Frequency distribution of exchange times

The non-conservative flux of DIP (ΔDIP according to LOICZ budget notation) is used as an approximation of net uptake of phosphorus into organic matter during primary production or net release from organic matter by respiration. The DIP flux is scaled to an estimated carbon flux via a scaling ratio (typically a molar C : P ratio of 106 : 1, representing the Redfield Ratio (Redfield 1958, Redfield et al. 1963). While it would be desirable to have direct measurements of carbon uptake into organic matter (Text Box 3.6), such data are not available for most locations. High precision is required for a good dissolved inorganic carbon (DIC) budget; such high precision data are rarely available, and certainly not available for most of the budget sites used here. Further, gas flux may dominate a DIC budget and be difficult to reconstruct from available data. Finally, processes such as calcium carbonate reactions and sulfate reduction complicate interpretation of DIC budgets. Therefore, as an alternative, the LOICZ approach uses ΔDIP as a proxy for net organic carbon flux.

One shortcoming of this proxy is that systems with high amounts of suspended mineral material (e.g., from rivers) may show evidence of DIP adsorption onto the particulate materials or desorption from them (Froelich 1988, Nixon et al. 1996). Further, systems with strong gradients in redox potential in the water column, such as

Text Box 3.7. Guidelines for constructing nutrient budgets of coastal systems

D.P. Swaney and S.V. Smith

These guidelines provide a basis for assessing whether or not information about a coastal ecosystem is reasonable in terms of general knowledge about natural science. Numerical values falling within these guidelines may be incorrect, but they are not immediately suspect. However, the further outside the guideline limits that the numbers fall, the more likely it is that an error exists in the values. These might involve erroneous calculations, erroneous assumptions or faulty data.

General knowledge and experience about the natural environment can inform the process of developing budgets. Some bounding of values may be obtained using simple scientific principles (such as the conservation of mass) and the overall comparison with many prior observations.

Hydrology

The total freshwater outflow to a coastal region (the sum of $V_Q + V_G + V_O$) is constrained by the net precipitation (rain + snowfall – evapo-transpiration) over the watershed (catchment) area of the coastal region. Therefore, over a sufficiently long time period (longer than the residence time of water in the catchment), riverine outflow plus groundwater flow to the sea should approximately equal the net precipitation over the catchment.

Exceptions to this rule occur in some areas, for example where groundwater is being "mined", i.e., extracted at a rate greater than it is being replenished by recharge, so the groundwater level is declining. While the mined water could be finding its way to the sea after use, a more likely possibility in arid environments is that it is being lost to evapo-transpiration. Except in the comparatively infrequent cases in which groundwater is a large term in the site budget, this is likely not to have a quantitatively significant effect on the water budget. Another possible violation of the rule is due to "inter-basin transfers" of water (water piped or channelled in from outside the drainage basin). For example, the New York City reservoir system lies partially outside the drainage area of the Hudson River (in the Delaware River basin). New York City discharges a large percentage of its sewage wastewater into the lower Hudson River estuary. The effect is an inter-basin transfer of water from the Delaware to the outflow of the Hudson River. An extreme transfer example, of course, is the diversion of the Colorado River flow to the city of Los Angeles and other destinations. A subtler effect is the alteration of the watershed hydrograph due to detention and evaporation of streamflow by reservoirs over the year or individual storm events.

Conventional estimates of evapo-transpiration may underestimate the loss of water associated with human activities, so caution should be exercised with these estimates for developed areas with large expanses of impervious surfaces, or other areas in which water is used extensively by the human inhabitants.

In any case, an upper limit on average freshwater flow to the sea is the product of average annual precipitation minus evapotranspiration (both in m) and catchment area (m^2). In most cases the flow will be dominated by surface runoff, loosely termed river flow. In environments with little or no surface flows to the sea, this figure should approximate the groundwater (subsurface) flows, especially in karstic bedrock conditions.

Maps of the global distribution of precipitation over the oceans are available from the IRI/LDEO Climate Data Library. Many maps of climatic and ecological variables over the continents may be found at the UNEP GRID websites (*http://www.grid.unep.ch/index.html* or *http://www-cger.nies.go.jp/grid-e/index.html*), including annual average precipitation and potential evapotranspiration (PET). Actual evaporation may be significantly lower than PET in desert areas because the lack of available water constrains the rate of evaporation. The GRID evapo-transpiration link contains a brief discussion of some methods to estimate evapo-transpiration from PET. For more information on precipitation and evaporation, examine the LOICZ Precipitation and Evaporation webpage (*http://www.loicz.org*).

Water and salt exchange with the sea

The term V_X used in LOICZ calculations represents a volume of water that effectively moves back and forth between the sea and the coastal system of interest, transporting salt with seawater concentration into the system from the ocean, and transporting salt at the system concentration back to the sea. Under the assumption of steady-state, this salt transport must be exactly equal and opposite to the transport of salt, at its concentration in the system, carried by V_R (i.e., the flow of water to or from the system to balance the freshwater budget). In fact, we use this relationship to estimate the value of V_X, and this suggests the magnitude of V_X even before calculation. First, while V_R may be positive (i.e., into the system, when evaporation or withdrawals from the system exceed sources) or negative (when freshwater flows exceed freshwater losses), V_X is always positive (by definition). Instances in which V_X may appear negative due to insufficient or inaccurate data sometime occur in hypersaline lagoons (in which salinity of the system should exceed that of the sea) subject to high evaporative losses of water. If the salinity difference between the system and the ocean appears to be positive and V_R also appears to be negative, then the ratio of $V_R : V_X$ is negative, yielding an estimate of V_X that is negative in sign. However, if the data are good, salinity will be elevated when V_R is positive and the resultant value for V_X will be positive. Bad data can result in inconsistent values for the salinity difference *and* V_R in either direction thereby resulting in (an incorrect) negative V_X.

Assuming that the estimate of V_X is positive, and V_R is negative (i.e., out of the system), what is a reasonable value? First, if annual averages are used and the system salinity is uncorrelated with freshwater flow, the salt flux associated with V_R is the product of system average salinity and V_R. The less saline the system, the greater V_R is relative to V_X. V_X is algebraically constrained to be numerically smaller than the magnitude of V_R if the system salinity is less than half of the oceanic salinity, and greater if the system salinity is greater than half-oceanic.

If seasonal data are available for salinity and V_R, then one can calculate their covariance, which is typically negative (during high freshwater flow periods, salinity drops, and vice versa). Because the salinity flux associated with V_R is the sum of this covariance and the product of average V_R and average system salinity, then this estimate of salinity flux is typically smaller than the previous estimate. Corresponding values of V_X should also be smaller.

From the standpoint of physical oceanography, V_X depends on several terms, including those associated with tidal exchange, density-driven currents, wind-driven currents, and frontal eddies. Gordon et al. (1996) provide formulas for estimating each of these four terms. Most of the time, only a single term is significant. For estuaries, with rare exception, V_X should be less than the tidal exchange volume, because tidal exchange does not operate with 100% efficiency and is usually the dominant contributor to V_X.

Oceanic salinity and nutrient data

Typical annual average values of salinity, nitrate (NO_3), phosphate (PO_4) and dissolved silicon (Si) for the global ocean at the sea surface and 1000 m depth are available from the superb website hosted by the Lamont-Doherty laboratory of Columbia University (IRI/LDEO Climate Data Library). The website also provides monthly datasets and values for various depths in the ocean; these data can be transformed and downloaded as tables or figures. Values for particular locations may also be examined, but caution should be exercised in their interpretation due to the coarse level of resolution of the dataset.

◀

Examination of the maps in the Climate Data Library suggest that significant variability exists in the "local ocean" even on an annual average basis (e.g., salinity values in the Baltic Sea, the "local ocean" for several important coastal ecosystems is typically around 7–8 psu, much lower than the 35 psu regarded as typical for the open ocean). At the surface, average annual nitrate concentrations at the sea surface can range from approximately zero (middle Atlantic and Pacific Oceans) to 25–30 µM (in the upwelling zone at 60 degrees South latitude). Generally, phosphate follows similar patterns, ranging from zero to around 2 µM (consistent with the Redfield ratio). Silicon ranges from zero to around 70 µM (with high values again in the > 60° N – 60° S latitude band). Along continental shelves, locally elevated regions exist due to the influence of coastal upwelling zones and riverine plumes. At depths well below the photic zone, inorganic nutrient concentrations typically increase because the biological sink associated with primary production is eliminated, while remineralisation of organic matter falling from the surface layer continues. Most of the sub-polar ocean registers average annual concentrations more typical of those seen at the surface in upwelling areas (NO_3 25–45 µM, PO_4 1.5–3.5 µM, Si 50–150 µM). The range of salinity narrows to a few psu because the influences of surface evaporation, precipitation and runoff are eliminated.

For budgeting purposes, an estimate of the mean salinity and nutrient concentrations over the depth of the sea likely to be exchanged with shallow coastal areas is most meaningful. When calculating budgets, values based on careful local measurements are always preferable to tabulated data from compendia. This is particularly true in the inner portion of the coastal zone because of local variations in the amount and composition of freshwater inflow. These compiled values are based on open shelf values and do not represent well this inshore variation.

Coastal ecosystem metabolism

Metabolism elements are laid out in an order that reflects likely knowledge about the system, first for carbon metabolism and then for nitrogen metabolism.

1. Primary Production (p) – in plankton-based systems, long-term (seasonal) primary productivity is typically 100–1 000 g C m^{-2} yr^{-1} (rounded daily rates of ~0.3–3 g C m^{-2} d^{-1}). While p can be somewhat lower or higher, values outside this range should be looked at with caution. For comparison with the biogeochemical calculations, these are expressed in molar rates: ~8–80 mol C m^{-2} yr^{-1}, 25–250 mmol m^{-2} d^{-1}. Systems dominated by benthic organisms (algae, seagrasses, mangroves, corals) may have primary production rates 2–3 times the upper limit for plankton.
2. Net Ecosystem Metabolism ($[p-r]$ or NEM) – the biogeochemical budgets, via ΔDIP, provide an estimate of net ecosystem metabolism, which is the difference between primary production (p) and respiration (r). That is, NEM = $[p-r]$. Ecosystems respire much of the organic matter that they produce and may (if there is an external source of organic matter) respire more than they produce. Values for p are frequently available, while r is much less frequently known but can be generally estimated. Typically p and r are within about 10% of one another. Assuming that p is known, this implies that the quantity $[p-r] = \pm 0.1p$. There can be exceptions to this, if the system receives extreme loads of either inorganic sewage nutrients or labile organic matter. However, for any system with $[p-r]$ outside the range $\pm 0.25p$, there is a strong possibility that either $[p-r]$ or (p) is in error.
3. Respiration (r) – rules 1 and 2 imply that r usually has about the same rate as p.
4. Nitrogen fixation (nfix) – this process is ordinarily slow in marine systems (< 1 mmol m^{-2} d^{-1}, < 400 mmol m^{-2} yr^{-1}). Most marine systems have no observable nitrogen fixation. Some coral reef, mangrove and tropical seagrass communities may exhibit rates 20 or more times this upper limit. As a general rule, though, few systems will have nitrogen fixation faster than this rate.
5. Denitrification (denit) – this process is apparently ubiquitous in systems with a significant rate of benthic metabolism and may occur in totally planktonic systems. The main requirement seems to be relatively rapid respiration, with benthic respiration being more efficient than planktonic respiration at promoting rapid denitrification. Typical rates in benthic systems would be around 0.5–2 mmol m^{-2} d^{-1} (200–700 mmol m^{-2} yr^{-1}), but systems with high benthic respiration (driven by either high primary production or high loading with labile organic matter such as sewage) may have denitrification rates > 10 mmol m^{-2} d^{-1} (or about 4 mol m^{-2} yr^{-1}).
6. Nitrogen fixation minus denitrification [nfix – denit] – This term expressing net nitrogen metabolism not directly associated with carbon metabolism involves the difference between nfix, as defined by item 4 above, and denit, defined by item 5 above. Unlike the situation with $[p-r]$ (1–3 above), [nfix – denit] are not necessarily strongly coupled. The implication is that the likely range of values for this process lies between maximum nitrogen fixation (~20 mmol m^{-2} d^{-1}, 8 mol m^{-2} yr^{-1}) and (minus) maximum denitrification (–10 mmol m^{-2} d^{-1}, –4 mol m^{-2} yr^{-1}). It follows from the discussion above, that a more typical range would be +1 to –2 mmol m^{-2} d^{-1} (+0.4 to –1 mol m^{-2} yr^{-1}).

the Scheldt Estuary, can show an important contribution of non-biological processes (such as iron oxyhydroxide precipitation/dissolution) to non-conservative fluxes of DIP. It should be noted that this DIP sorption/desorption problem is most likely to be an issue in river-dominated systems, with large amounts of inorganic sediment, but it is not a major issue in most open-shelf settings. A second issue, also largely restricted to inshore systems, is the choice of an appropriate C : P scaling ratio. For example, benthic algae, seagrasses and mangroves all have carbon : nutrient ratios very different from the Redfield Ratio (Atkinson and Smith 1983). In general, terrigenous organic matter associated with vegetation has high C : nutrient ratios, while organic matter associated with organic waste is low in C : nutrient ratios (Vitousek et al. 1988, San Diego-McGlone et al. 2000). On the open shelf, dominated by planktonic systems, phytoplankton may legitimately be assumed to be the dominant form of reacting organic matter.

The relative influence of terrestrial/atmospheric loads and oceanic fluxes varies enormously across systems. On the terrestrial side, the level of influence depends upon the relative size of the associated drainage basin and level of human development, among other factors. On the oceanic side, the relative intensity of exchange (physical processes) is important as well as the quality (e.g., primary production and/or nutrient concentrations) of the oceanic end-member. Because these balances are sensi-

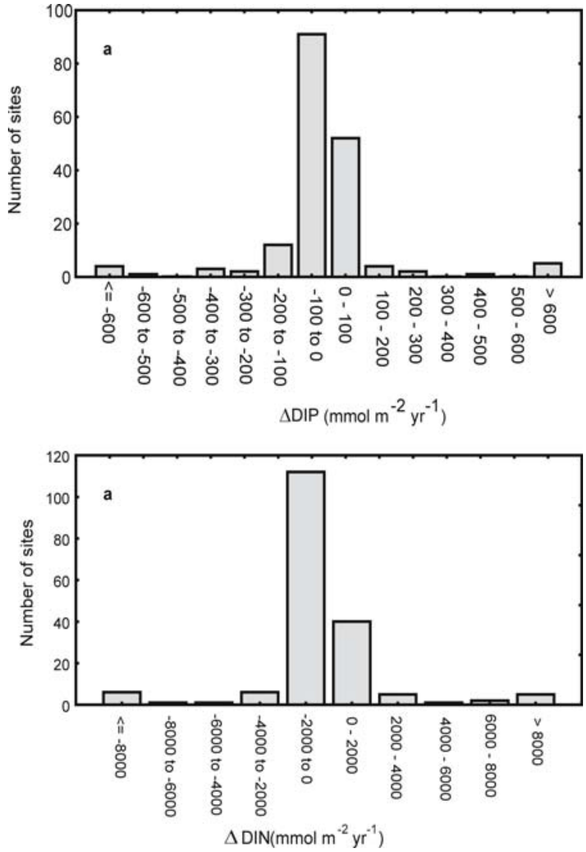


Fig. 3.10. Budget sites. Frequency distributions of (**a**) ΔDIP and (**b**) ΔDIN

tive to system size, as measured directly by area, depth or volume, or indirectly by residence time, we expect relationships between these measures to emerge by analysis of the defining equations. We hope that by studying the departures from these expected relationships observed in the actual data, insight may be gained into the relationships between the non-conservative fluxes and size of the system. We wish to establish relationships not only between the magnitude of the non-conservative fluxes and the driving variables, but also between the sign of the flux and the driving variables.

3.2.3.1 *Distributions of ΔDIP and ΔDIN*

The frequency distributions of the non-conservative fluxes of P and N (Figs. 3.10a, b) reveal a strong peak centred near zero, but with a bias to the negative side, indicating that, on average, a few more sites function as net internal sinks of both nitrogen and phosphorus than as sources. Following conventional LOICZ interpretation, this suggests a slight bias both toward autotrophy and toward a net denitrification over nitrogen fixation. It is important to note, however, that area and volume of the sites are not taken into account in this analysis, so that the actual balance of these processes for the overall coastal zone may not be accurately reflected by this interpretation.

3.2.3.2 *Some Relationships between Variables Controlled by LOICZ Methodology*

There are several relationships between variables imposed by the defining equations for non-conservative flux estimates (Text Box 3.8). While it is possible to derive many of such relationships from the LOICZ methodology, we examine two obvious candidates here: (*i*) limitations from relationships between non-conservative fluxes and the degree of terrestrial/oceanic influence, and (*ii*) the relationships between these fluxes and the system's water residence time (exchange time). Details of these approximations, including a discussion of terrestrial and oceanic dominance, are shown in Text Box 3.8.

3.2.3.2.1 *Non-conservative Fluxes and Terrestrial/Oceanic Dominance*

For systems dominated by ocean exchange, we can conclude from the imposed relationships that:

- The sign of ΔDIP (and thus the signal of its autotrophic/heterotrophic status) will be determined by the sign of the system-ocean concentration gradient.
- In the absence of a strong correlation between V_X and the system-ocean concentration gradient, a log-log plot of ΔDIP versus V_X should have a slope of +1 i.e.,

$$\log \Delta\mathrm{DIP} \cong \log(V_X) + \log(\mathrm{DIP}_{sys} - \mathrm{DIP}_{ocn})$$

- If there is a significant correlation between V_X and the system-ocean concentration gradient (or more properly, between their log values), then this should be expressed in the slope of the log-log plot.

Conversely, for systems dominated by terrestrial loads, we can conclude from the imposed relationships that:

- The sign of ΔDIP will be determined by the sign of the concentration gradient between the terrestrial load and the residual flow.
- In the absence of strong correlations between V_R and the concentration gradient in the first term, a log-log plot of ΔDIP vs V_R should have a slope of +1.
- If there are significant correlations between V_R and the concentrations, then this should be expressed in the slope of the log-log plot.

3.2.3.2.2 *Non-conservative Fluxes and Exchange Time*

If we eliminate V_X from the budget expressions and express the relationship with ΔDIP in terms of water resi-

Text Box 3.8. Imposed relationships between LOICZ budget variables

D. P. Swaney

The budget methodology provides an estimate of non-conservative fluxes in terms of the driving variables. The "algebra" of these relationships (Text Box 3.4) can suggest the factors that dominate the behaviour of these estimates under various limiting conditions, thereby providing clues in the search for patterns.

Non-conservative fluxes and terrestrial/oceanic dominance

Consider dissolved inorganic phosphorus (DIP) as an example. Defining DIP_{Load} as the flow-weighted average concentration of DIP from all terrestrial and atmospheric sources (losses of DIP through water evaporation are assumed to be negligible, as $DIP_E = 0$), then:

$$DIP_{Load} \equiv \frac{-1}{V_R}(V_Q DIP_Q + V_O DIP_O + V_P DIP_P + V_G DIP_G) = \frac{\sum V_i DIP_i}{\sum V_i}, \quad i \in \{Q,O,P,G\} \qquad (1)$$

Substituting, we obtain the simple result:

$$\Delta DIP = V_R\left(DIP_{Load} - DIP_R\right) + V_X(DIP_{sys} - DIP_{ocn}) \qquad (2)$$

or, in terms of the terrestrial/atmospheric flux of DIP:

$$\Delta DIP = \left(FLUX_{DIPLoad} - V_R DIP_R\right) + V_X(DIP_{sys} - DIP_{ocn}) \qquad (3)$$

In the above expression, we see that the estimate of non-conservative DIP flux is expressed as the sum of two terms, representing gradients of nutrient fluxes. The first term is a product of the system residual flow (V_R) and an effective gradient of DIP concentrations between the terrestrial loads and the residual nutrient flux (Eq. 2), and the second, the product of the DIP system-ocean concentration gradient, and the system mixing volume (V_X). The structure of this relationship suggests a natural "partitioning" of the variables in which to look for patterns.

If the first term is negligibly small compared to the second term (i.e., ΔDIP is *ocean-exchange dominated*), then

$$\Delta DIP \cong +V_X(DIP_{sys} - DIP_{ocn})$$

Alternatively, if the first term is large compared to the second term(i.e., *terrestrial-load dominated*), then

$$\Delta DIP \cong (FLUX_{DIPLoad} - V_R DIP_R)$$

These simplifications can be interpreted in terms of controls on autotrophy and heterotrophy (see text).

Non-conservative fluxes and exchange time

We can also eliminate V_X from the above expressions to express the relationship in terms of the system water residence time (τ):

$$\Delta DIP = V_R\left(DIP_{Load} - DIP_R\right) + \left[\frac{V_{Sys}}{\tau} - |V_R|\right](DIP_{sys} - DIP_{ocn}) \qquad (4)$$

For positive estuaries ($S_{sys} < S_{ocn}$, $V_R < 0$):

$$\Delta DIP = V_R(DIP_{Load} - DIP_R + DIP_{sys} - DIP_{ocn}) + \frac{V_{Sys}}{\tau}(DIP_{sys} - DIP_{ocn}) \qquad (5)$$

For negative estuaries ($S_{sys} > S_{ocn}$, $V_R > 0$):

$$\Delta DIP = V_R(DIP_{Load} - DIP_R - DIP_{sys} + DIP_{ocn}) + \frac{V_{Sys}}{\tau}(DIP_{sys} - DIP_{ocn}) \qquad (6)$$

Here, the first term is the product of V_R and a sum of the DIP concentrations of the load, system, residual flow and ocean. These concentrations represent the difference between the gradients of concentration between the load and the residual flow, and the system and the ocean. As such, they are a "gradient of two gradients" of concentration, somewhat analogous to the second-spatial derivative of concentration seen in models of diffusive exchange. Thus, the first term should be sensitive to differences in the concentration gradient between the load and the system, and the system and the ocean, such as might occur in spatially extensive systems. The second term is the product of the DIP system-ocean concentration gradient, and the ratio of system volume to exchange time.

Here, if the *first term is small* compared to the second term, then

$$\Delta DIP \cong +\frac{V_{Sys}}{\tau}(DIP_{sys} - DIP_{ocn})$$

suggesting a significant negative relationship with exchange time. Alternatively,

$$\Delta DIP = V_R\left((DIP_{Load} - DIP_R) \pm (DIP_{sys} - DIP_{ocn})\right)$$

suggesting that the balance of gradients between terrestrial and oceanic boundaries is dominant.

dence time (τ), we can approximate limiting behaviour with respect to τ, i.e., the smaller the value for τ, the smaller the change in DIP concentration associated with any particular non-conservative change in DIP (represented as ΔDIP). If residual flow is relatively small, or the concentration gradient between terrestrial sources and the coastal system is not much different than that between the system and the local ocean, then:

- The sign of ΔDIP (and thus, the signal of its autotrophic/heterotrophic status) will be determined by the sign of the system-ocean concentration gradient.
- In the absence of strong correlations between τ and the other variables of the second term, a log-log plot of ΔDIP versus τ should have a slope of −1.
- If there are significant correlations between τ and the other variables of the second term (or more properly, between their log values), then this should be expressed in the slope of the log-log plot.

Conversely, the balance of concentration gradients should dominate and:

- The sign of ΔDIP will be determined by the sign of the "gradient" of the concentration gradients associated with terrestrial load/residual flux and system/ocean concentrations.

- In the absence of strong correlations between V_R and the concentrations in the first term, a log-log plot of ΔDIP versus V_R should have a slope of +1.
- If there are significant correlations between V_R and the concentrations, then this should be expressed in the slope of the log-log plot.

3.2.3.3 *Additional Relationships between Variables*

Here, we examine a few relationships between the budget variables suggested by the above analysis. In doing so, we have log-transformed the data presented in the figures because (*a*) the great range in the magnitude of the variables suggests the use of the log-transformation to stabilise variance when performing statistical analysis and (*b*) we may be able to test predictions of some coefficients of linear relationships observed in log-transformed data, at least for some subsets of the data (see Text Box 3.9).

3.2.3.3.1 *Water Exchange Time and System Area*

In broad terms, water exchange is driven by the combination of advective inflow and outflow, and mixing. For embayments ranging from a small inlet to a large enclosed sea such as the Baltic, the model works well and the advection (in and out) is defined by the freshwater balance. Mixing must balance the advective flux of salt. For the most part our data represent such an embayment structure. Budgets would not be expected to work well in a classical open shelf (unless the shelf is considered to be infinite in length and the transports to be cross-shelf transports). Nevertheless, we suggest that biogeochemical processes (the primary interest of this research) work similarly on open shelves as in more well-defined systems such as the southern North Sea, the Irish Sea and the East China Sea. We have attempted budgets of narrow upwelling shelves of both South America and South Africa with minimal success (e.g., Hall et al. 1996).

For the systems we have budgeted, Fig. 3.11 shows a noisy but clear relationship between budgeted area and

Text Box 3.9. Regression techniques for estimating functional relationships between variables

D. P. Swaney

The most popular method of fitting a line to a set of data is simple linear regression, in which the slope and y-intercept of the line are determined by minimising the squared deviations of the *y*-data from the line. Multiple regression is generally used if there are two or more dependent variables. It is important to recognise that simple linear regression can introduce bias in the slope estimate if the *x*-data are also subject to measurement error (see Sokal and Rohlf 1995). If both the *x* and *y* (the independent and dependent variables) are subject to the same types of errors, the data are often better analyzed using a "Model II" type regression which uses the deviations of both *x* and *y* from the line of best fit (Figs. TB3.9.1 and TB3.9.2). Ricker (1973) recommends a specific type of Model II regression, called Geometric Mean (GM) or Reduced Major Axis (RMA) regression, for such cases (Ricker 1973, Sokal and Rohlf 1995, Laws 1997). We have used the GM regression wherever feasible to examine linear relationships between the log-transformed variables, using a simple Excel™ spreadsheet add-in developed by Sawada (*http://www.uottawa.ca/academic/arts/geographie/lpcweb/newlook/data_and_downloads/download/sawsoft/modelii/modelii.htm*) and modified by Swaney to estimate corresponding approximate confidence intervals (Ricker 1973). The modified add-in is downloadable from the LOICZ website (*http://data.ecology.su.se*). For regressions involving more than one independent variable, we use conventional multiple regression, though future efforts may involve more sophisticated techniques, including principal components analysis, and principal components regression (see Dunteman 1989). More sophisticated statistical classification capability is available through the LOICZView, discussed in Chap. 1.

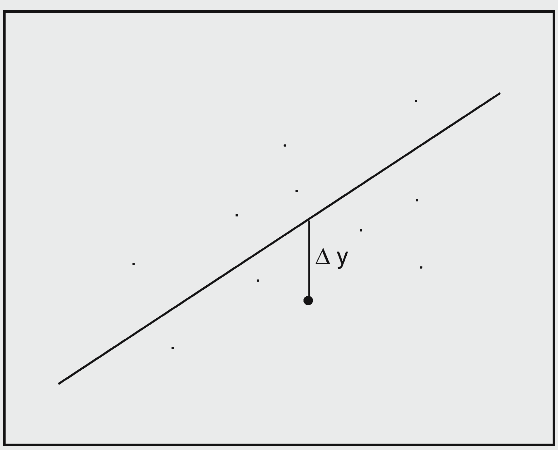


Fig. TB3.9.1. Vertical (Δ*y*) deviation of a data point from the best fit line, the sum of which is minimised in simple linear regression

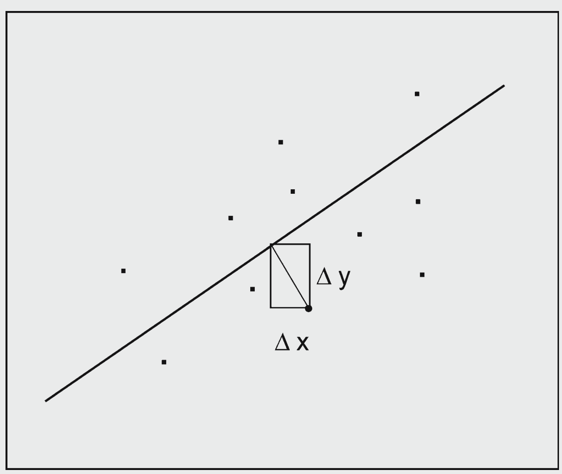


Fig. TB3.9.2. Rectangle associated with the normal deviation of a data point from the best fit line ($\Delta x^2 + \Delta y^2$), the sum of which is minimised in Model II regression. The line bisecting the rectangle is at 90° to the best fit line water exchange time. For systems smaller than about 100 km^2, there is no strong pattern but a range in exchange times between about 1 and 100 days. For systems larger than 100 km^2 there appears to be a clear trend of increasing exchange time with size. Systems larger than a few thousand km^2 typically have exchange times in excess of a year, e.g., the North Sea (area ~300 000 km^2, exchange time 370 days), the East China Sea (area ~900 000 km^2, exchange time 490 days).

3.2.3.3.2 *Internal Processes and Exchange Time*

Water exchange time is a measure of renewal time. Systems with a long exchange time retain materials long enough to react internally; systems with a short exchange time are simple conduits through which water flows. The budgeted systems range in exchange time from < 1 day to many years.

The figures illustrate non-conservative fluxes of both DIP and DIN (Figs. 3.12a–d), as well as the derived estimates of $[p - r]$ and [nfix – denit] (Figs. 3.13a–d) as functions of water exchange time (τ_X). The patterns that emerge are very noisy, but not inconsistent with the arguments based on the mass balance equations expressed above. All of these non-conservative variables show a negative log-log relationship with τ_X, and a slope not too different from –1. Assuming that this indicates that the first term in Eqs. 5–6 of Text Box 3.8 is relatively small, then it follows that the sign of ΔDIP or ΔDIN should be given by that of the ocean-system nutrient gradient. For ΔDIP, it follows that the sign of this gradient should be a dominant factor in determining autotrophy versus heterotrophy.

This hypothesis about control over metabolism was examined further by dividing the budget sites into two categories: those with a system-ocean nutrient concentration difference > 0, and those with a concentration difference ≤ 0, considering both DIP and DIN concentrations. Statistical *t*-tests were applied to the mean values of ΔDIP and ΔDIN for each category to determine if these were significantly different from each other (both regular and log-transformed magnitudes with sign preserved were tested). Irrespective of the log-transforma-

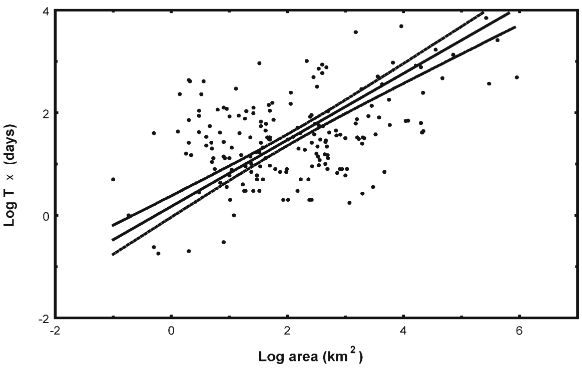


Fig. 3.11. Budget sites. Exchange time versus system area (Model II regression line with 95% confidence: $y = 0.17 + 0.65x$, $r = 0.46$, $n = 184$)

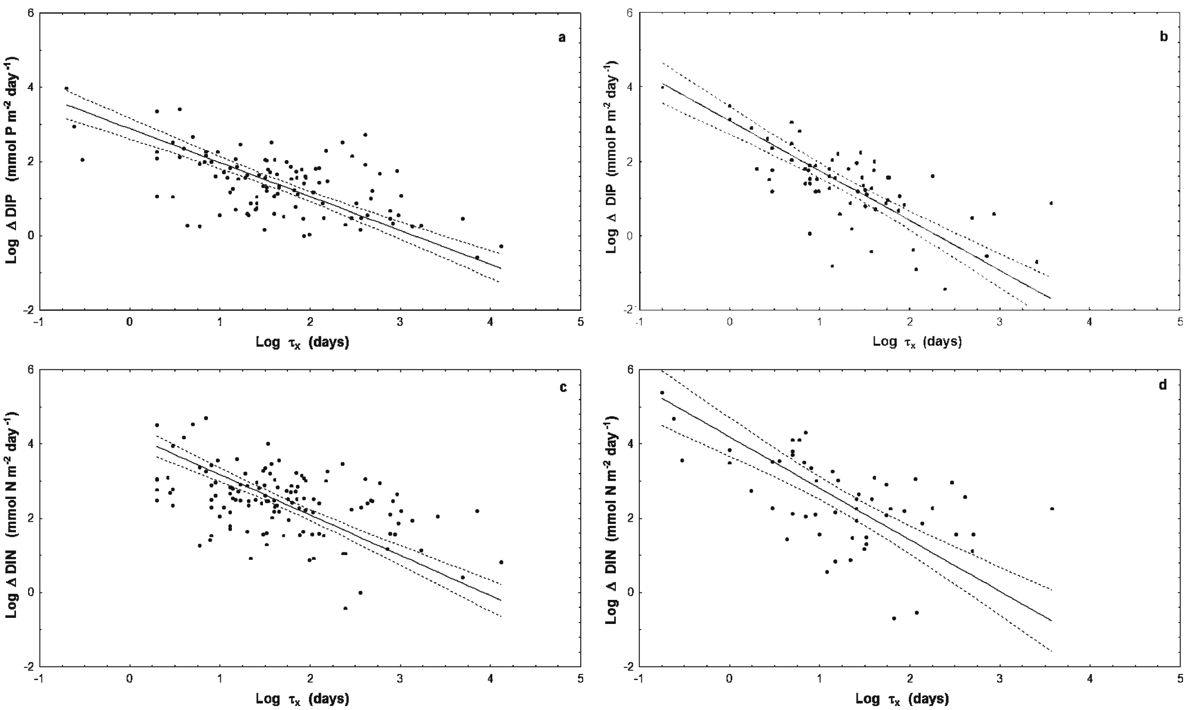


Fig. 3.12. Budget Sites. ΔDIP and ΔDIN as functions of system exchange time (Log-log plots; Model II regression line with 95% confidence). **a** ΔDIP < 0 ($y = 2.89 - 0.91x$, $r = -0.54$, $n = 107$); **b** ΔDIP > 0 ($y = 3.09 - 1.34x$, $r = -0.68$, $n = 65$); **c** ΔDIN < 0 ($y = 4.26 - 109x$, $r = -0.45$, $n = 124$); **d** ΔDIN > 0 ($y = 4.19 - 1.39x$, $r = -0.53$, $n = 51$)

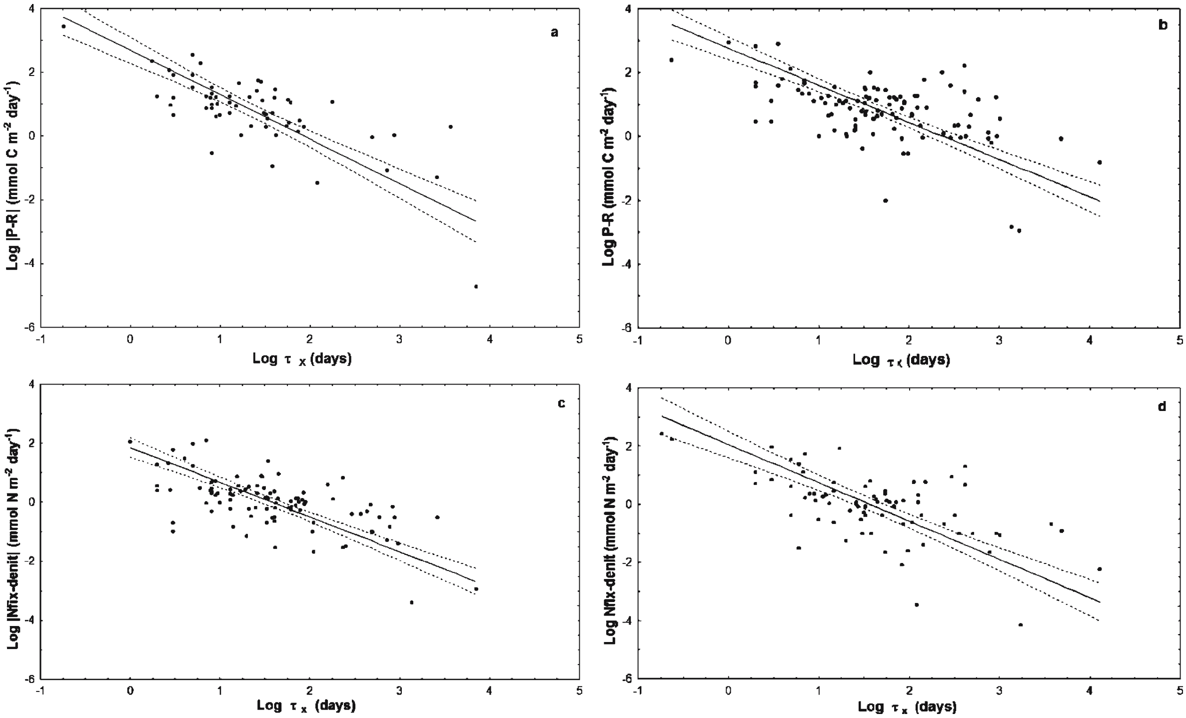


Fig. 3.13. Budget Sites. Apparent net ecosystem production $[p - r]$ and apparent nitrogen fixation minus denitrification [nfix – denit] as functions of system exchange time (Log-log plots; Model II regression line with 95% confidence). **a** $[p - r] < 0$ ($y = 2.68 - 1.39x$, $r = -0.73$, $n = 59$); **b** $[p - r] > 0$ ($y = 2.74 - 1.15x$, $r = -0.52$, $n = 104$); **c** [nfix – denit] < 0 ($y = 1.85 - 1.18x$, $r = -0.64$, $n = 96$); **d** [nfix – denit] > 0 ($y = 2.05 - 1.32x$, $r = -0.60$, $n = 75$)

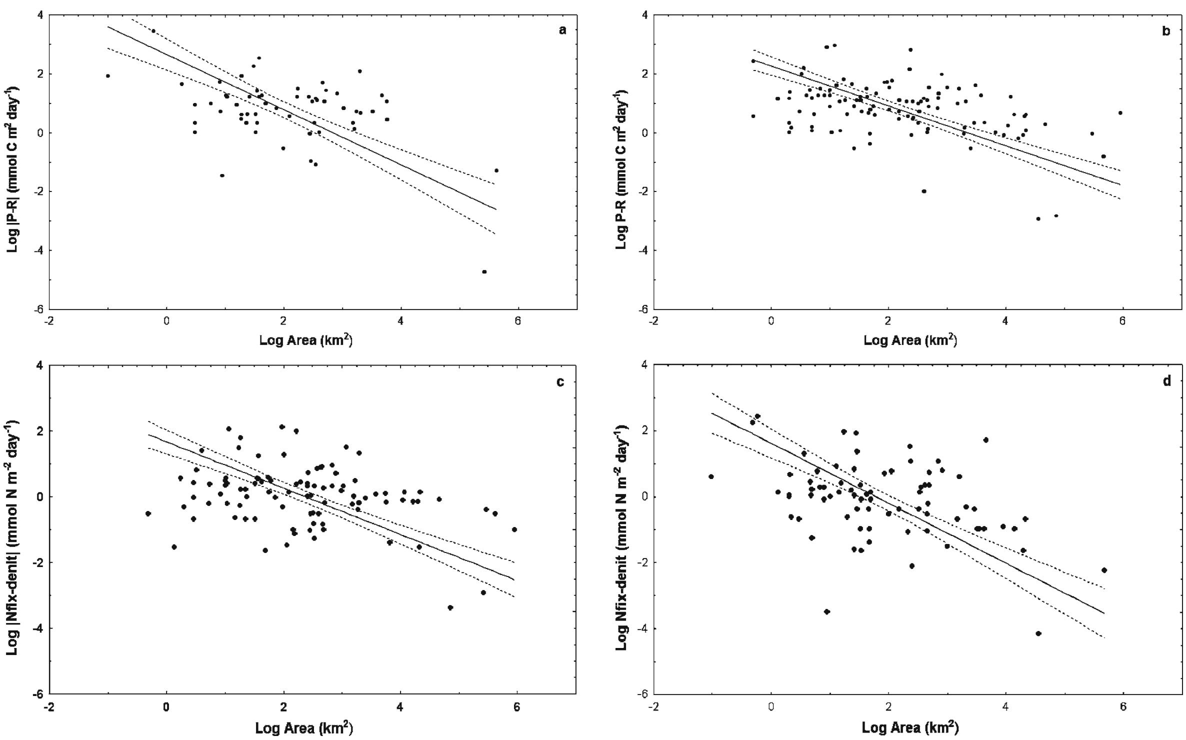


Fig. 3.14. Budget sites. Apparent net ecosystem metabolism $[p - r]$ and apparent nitrogen fixation minus denitrification [nfix – denit] as functions of system area (log-log plots; Model II regression line with 95% confidence). **a** $[p - r] < 0$ ($y = 2.65 - 0.94x$, $r = -0.46$, $n = 58$); **b** $[p - r] > 0$ ($y = 2.26 - 0.68x$, $r = -0.42$, $n = 105$); **c** [nfix – denit] < 0 ($y = 1.67 - 0.70x$, $r = -0.31$, $n = 97$); **d** [nfix – denit] > 0 ($y = 1.62 - 0.91x$, $r = -0.40$, $n = 76$)

tion, ΔDIP was found to exhibit significantly different values depending upon the sign of either the DIP or DIN nutrient gradient, and ΔDIN was not. In other words, ΔDIP (and accepting the LOICZ assumptions, net ecosystem metabolism) appears to be sensitive to the sign of the system-ocean nutrient gradient, but ΔDIN does not. A possible interpretation is that for ΔDIN, the oceanic-system gradient may not be as dominant a variable; terrestrial sources of DIN may play a significant role.

Regardless of the complexities of the interactions of nutrient loads, exchange and residence time, most of the observed non-conservative behaviour (either as net sources or sinks) for these systems occurs at exchange times < 100 days and system areas of < 1 000 km^2 (Figs. 3.13, 3.14). One interpretation of this result is that smaller coastal systems (as opposed to larger, shelf seas) are the dominant engines of coastal zone metabolism. Whether the cumulative effects of the nutrient processing of many small high-output systems dominate those of relatively few large but less intense systems remains to be seen.

3.3 Classification of Coastal Fluxes

3.3.1 Budget Sites and Coastal Areas: Sizes, Scales and Representation

The types and sources of the data used, conceptual approaches and tools are discussed in Chap. 1. Here we consider the classification approaches applied to develop patterns of coastal fluxes in the global coastal zone in terms of categories, processes and the variables available for use.

Two major data constraints have shaped the approaches and outcomes and are central to the discussions that follow. First, the global database used for coastal zone classification (typology) is based on a gridded system of half-degree (0.5°) latitude and longitude boxes. Although this resolution is dictated by the scale of many of the globally available datasets and the need to make the databases available over the internet, it is too coarse to resolve many of the important coastal zone features and smaller budget sites. This imposes significant limitations on the upscaling processes and short-term potential, and points to obvious areas of potential improvement and extension (see Recommendations). Another aspect of this choice of gridding is that the relationship between distance in kilometers and degrees of longitude is a non-linear function of latitude (see Text Box 1.7, Chap. 1), so the grid cells are not equal in area, and biases could be introduced by some cell-based comparisons or calculations.

The second constraint, which interacts strongly with the first, is that the coastlines of the world are mostly dominated by small, local drainage basins, whereas most of the knowledge about the characteristics of riverine input to the coastal zone is generated from relatively few, better-studied large and medium-sized river systems (Milliman and Syvitski 1992). While the total discharge and nutrient flux *to the ocean* is dominated by large rivers, the direct effects of high volume inputs (i.e., large rivers) *on the coastal zone* are very localised. The greatest length of coastline, the largest volume of coastal water (Text Box 1.1, Chap. 1), and quite possibly the overall nature of biogeochemical fluxes, strongly reflect smaller and more locally-derived inputs of rivers, groundwater and other freshwater sources. Thus, the most important features of the coastal zone probably include those systems that are least accurately described, both in general and by the half-degree data resolution used for typology.

In order to consider the potential for upscaling to regional and global contexts or generalising results based on the budget and typology datasets, we consider both the nature of the variables available and the physicochemical forcing functions and inputs to the coastal zone from both land and ocean. Particularly on the terrestrial input side, the distinction between anthropogenic influences and natural inputs is critical to understanding both present and possible future dynamics. In considering both the land-ocean and human-natural dichotomies, two further critical questions arise: (*1*) how well and how effectively can we define and classify "small" coastal basins, and predict their functions, in a data environment with resolution limited to 0.5°; (*2*) how well does the LOICZ budget dataset represent the world's coastline?

3.3.2 Land versus Ocean Dominance of Biogeochemical Processes: Dynamic Factors in Coastal Classification

The relative dominance of the biogeochemical budget variables by land and ocean influences is discussed and illustrated in Sect. 3.2.2 and Text Box 3.8. In order to upscale these observations, they must be expressed in terms of, or correlated with, more generally available environmental variables with well-characterised coastal zone distributions. Physical forcing (fluxes and exchange times of water) will determine the relative dominance of land and ocean with respect to supplying nutrient inputs; the nature of those inputs will be determined by the concentrations of nutrients in the source waters.

Three major factors that determine overall physical forcing are:

- Hydrologic (terrestrial) forcing – runoff, primarily in the form of river discharge, but with potential contributions from groundwater discharge and diffuse surface runoff. This physical forcing may be a conduit for a variety of chemical components of both human and natural origin.
- Ocean forcing – waves, tides and currents.

- Coastal openness or exposure – the geomorphology of the coastal system, in terms of depth, orientation and coastal complexity, a major factor in how these driving forces determine the critically important residence time of the system that in turn modifies the rates and extent of the biogeochemical reactions (Bartley et al. 2001).

3.3.2.1 *Oceanic Forcing*

Physical forcing of the system water exchange time – the turnover rate of the biogeochemical reactor – is determined by water flux. From the marine side, this reflects the combined effects of currents. For very large systems or open shelf settings, regional oceanic currents may be important as physical drivers, just as upwelling zones may be important to the supply of oceanic nutrients (Nixon et al. 1996, Michaels et al. 1996). For small and intermediate-sized budget systems, effects of tidal and wind-driven currents are likely to be particularly important to local water exchange and mixing. The typology database does not contain information on larger-scale oceanic system currents at present. For most of the duration of the LOICZ project, available global data on wave height and tidal range have been limited to rather coarsely classified datasets with relatively sparse coverage. However, recent acquisition of much more detailed marine wind data (da Silva et al. 1994) and tide model outputs (Stewart 2000) have permitted classification of the smaller-scale forcings with greater confidence. While these provide an incremental shift in the typology database capacity, it should be noted that the scale and resolution of the additional tidal and wind data characterise open coastal conditions. Their application as proxies for water processes in small or semi-enclosed embayments is less certain.

Figure 3.15 shows LOICZView clustering classifications of two marine energy proxies, a tidal flushing index (maximum amplitude multiplied by a form factor representing diurnal/semidiurnal frequency) and the square of the average wind speed (as an index of wind stress). Also shown is the average depth of the coastal cells, which strongly conditions the transmission of water and energy. For the energy variables, the colour index ranges from red at high values (higher winds, higher tides, greater flushing) to blue for calmer conditions. For depth, red indicates shallow water, while blue is deeper. Using six or seven categories, this classification approach demonstrates the spatial continuity of the marine forcing variables and illustrates the potential for combining the variable classifications into a more general multivariate exchange or energy index.

Marine forcing variables tend to have rather smooth spatial distributions at scales of tens of kilometers and above in the offshore environment (ocean and open shelf), in part due to data resolution and in part due to apparent spatial heterogeneity of the land. This pattern holds for the distributions of precipitation and evaporation and other climate-controlled variables. These parameters can be described and analysed well at the half-degree level. However, application to specific budget settings becomes more problematic because of the effects of local coastal structure that can strongly modify the forcing functions and especially their interactions.

3.3.2.2 *System Size, Complexity and Exposure*

The physical configuration of a coastal system is the critical link between the terrestrial and the marine forcings.

For classification and upscaling, the essential issue is the relationship of system size to the half-degree typology database grid, and to the resolution of the component geomorphic variables in the database. There are strong analogies between coastal system size and catchment basin size; systems or basins with areas in the 1 000–10 000 km^2 range are likely to be described reasonably well by the characteristics of the corresponding grid cells, while smaller systems are less likely to be well-represented by half-degree variables unless they are particularly open and well-connected with the offshore environment. Figure 3.4 illustrates the distribution of system size (areas) of budget sites; almost 75% of the systems analysed are <1 000 km^2 in area, and only about 15% are in the typologically optimal 1 000–10 000 km^2 range.

System configuration – shape, complexity, exposure – has three major components readily identifiable in terms of typology:

- Depth – the depth of a system and its immediate surroundings exerts strong control over the dissipation and distribution of tidal and (especially) wave energy, and on the amount of light reaching the benthic ecosystems.
- Coastal complexity – convoluted or compartmentalised systems are likely to be both heterogeneous and relatively protected from the effects of the marine physical forcing functions.
- Orientation and relationships – the relationships of wind and current direction to coastline orientation determine both the degree of "exposure" of a system and the magnitude of its oceanic exchanges. Offshore environmental factors such as bottom slope or the presence/absence of shoals and barriers also strongly mediate interactions between systems and the more broadly distributed forcing functions.

Although the distribution of budget sites characterised to date is concentrated well below the scale of the current typology grid system, the key geomorphic variables have underlying resolutions much more appropri-

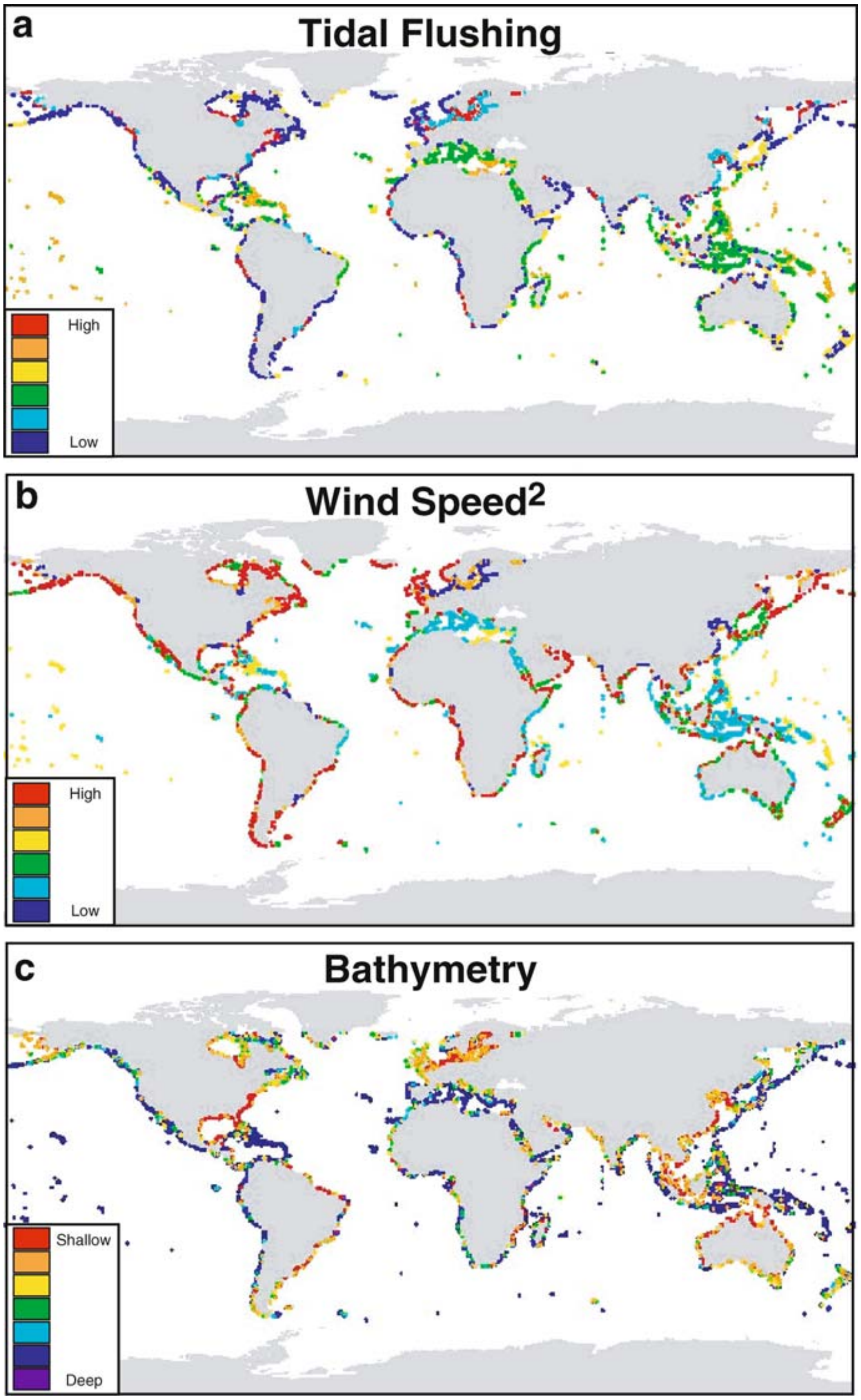


Fig. 3.15. Classification of proxy variables for ocean forcing. **a** LOICZView clustering of a tidal flushing index for coastal and adjacent Ocean I cells. Intensity of potential tidal flushing increases from *blue* (lowest) through *red* (highest). **b** LOICZView clustering of wind speed squared for coastal and adjacent Ocean I cells. Mean wind speed (and hence wave-induced mixing and wind-driven currents, represented by velocity squared) increases from *blue* (lowest) through *red* (highest). **c** Clustered distribution of mean depth of coastal cells. *Blue cells* are deepest, *red* are shallowest

ate to the necessary characterisation. The World Vector Shoreline data has both directionality and sub-kilometer scale resolution, and the ETOPO2 bathymetry database has pixel sizes of 2' (4 km or less, depending on latitude). Additionally, the wind data in use have vector as well as scalar components, although these have not been incorporated into the database.

The present half-degree database system includes sub-grid scale information about the component variables. Coastline length and total land and water areas within the cells are examples of data that provide information about characteristics within the cells. The typology database also contains statistics on depth distributions of the 2' pixels within the half-degree cells (mean, maxi-

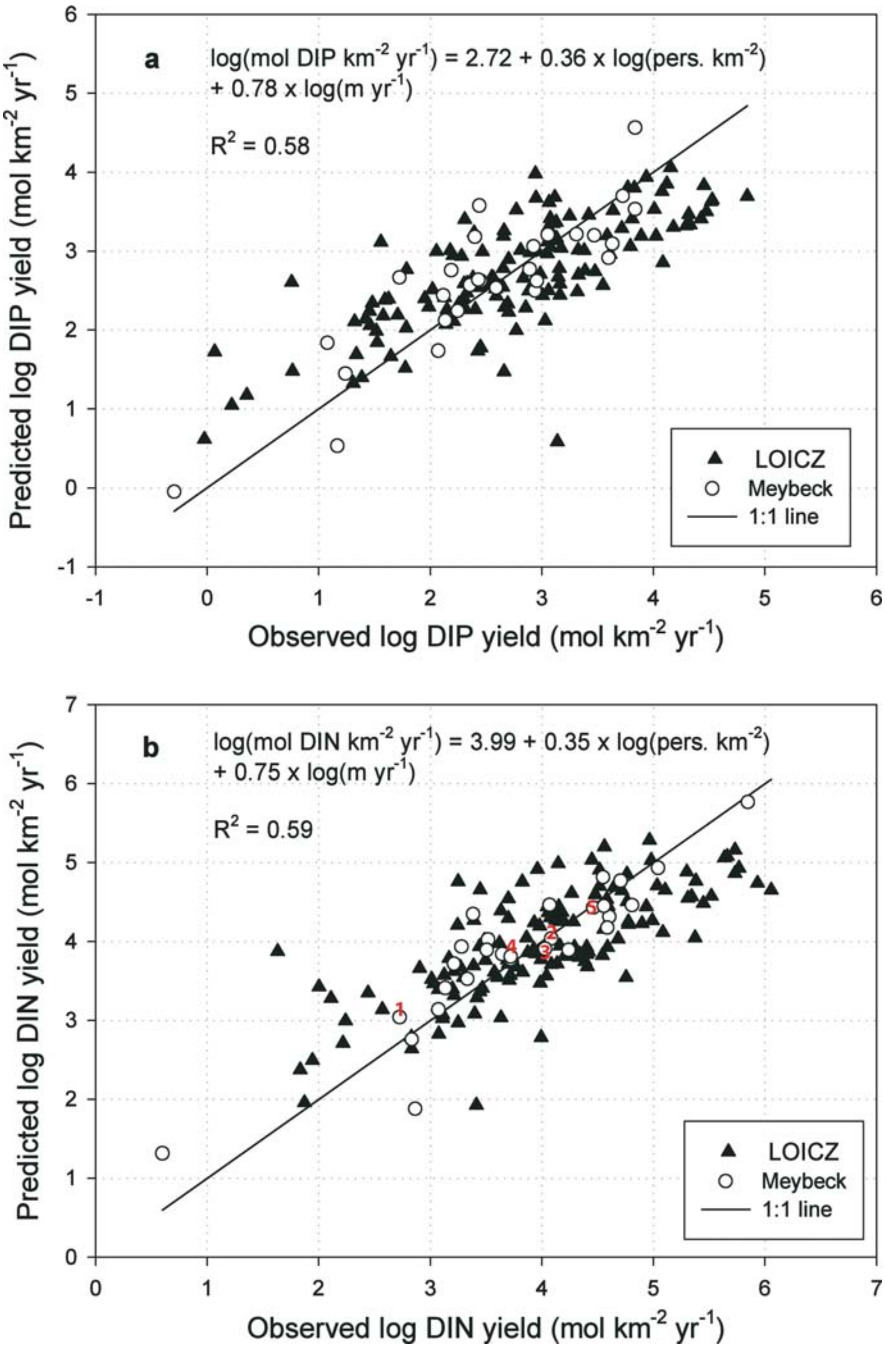


Fig. 3.16.
Nutrient loading – loads to coastal systems. Observed versus predicted values for (**a**) DIP and (**b**) DIN loading (from Smith et al. 2003). *Triangles* represent LOICZ budget sites; *circles* represent Meybeck (1982) basins. The five largest basins are identified by number: *1* Amazon; *2* Congo; *3* Rio de la Plata; *4* Amur; *5* Changjiang

mum, minimum, standard deviation); these provide within-cell estimates of features such as slope and heterogeneity. However, limitations of the datasets need to be considered; the absolute accuracy of the ETOPO2 pixel depths is much less than the nominal 1 m depth resolution provided.

Overall, the complexity parameters are among those that are currently problematic but that offer opportunities for rapid progress in coastal zone classification and typology applications (Bartley et al. 2001, see Text Box 1.1, Chap. 1).

3.3.2.3 *Hydrologic (Terrestrial) Forcing*

The hydrologic forcing variables from the budget datasets that contribute to the total freshwater flow are V_Q (stream discharge), V_G (groundwater discharge), V_P (precipitation), V_E (evaporation), and V_O (point discharges) (see Text Box 3.4 for definitions). In most situations V_Q is volumetrically dominant. The typology database lacks variables that can estimate or correspond to V_G and V_O; V_P and V_E are represented by corresponding environmental datasets, but have not been applied to typologies developed to date. The typology variable equivalent to the important V_Q variable is basin runoff (RO); the RO data are derived from water balance models and might more accurately be termed "potential runoff". For many applications we use the catchment area (A)-normalised values of these volumes, V_Q/A or RO/A, in units of m yr^{-1}.

The typology catchment basin variables were augmented with refined basin data for the catchments associated with most of the localised budget sites, developed by using GIS techniques and the Hydro1K (USGS 2001) dataset, to produce catchment basin polygons. These are identified as the km-scale basins and were used to determine the basin area and to sample other areally-distributed variables (Buddemeier et al. 2002, Smith et al. 2003). Of particular relevance to the discussions that follow are runoff-related variables, human population and population density. In most cases, km-scale basins could be directly identified with a corresponding half-degree basin or cell. The values of the variables sampled at the basin scale were not only used for analysis of the budget variable relationships (see Sect. 3.3.3), but also for examining issues of basin scale and the degree to which the present biogeochemical budget sites may represent either the global distribution of sites or their functional processes (Text Box 3.12; Sect. 3.3.5).

3.3.3 Natural and Anthropogenic Factors: Pristine to Highly Altered

3.3.3.1 *Combined Controls on Nutrient Loads and Anthropogenic Factors*

Climatically-driven forcing functions, such as runoff, interact with land cover, land use and geomorphology to modulate inputs to the coastal zone that result from a mixture of natural processes and varying degrees and types of anthropogenic modifications.

For the km-scale budget site basins, Smith et al. (2003) have observed a logarithmic relationship between DIP and DIN loads, and the population density and area-normalised discharge (Fig. 3.16; see also Buddemeier et al. 2002). This robust finding substantially extends and is consistent with many studies (e.g., Meybeck and Ragu 1997) and provides a useful starting point both for further refinement of the relationship in terms of climate and land use, and for consideration of upscaling the terrestrial inputs to the ocean on the basis of readily available terrestrial data.

Influences of human activities within river basins are encapsulated by both the population density and runoff terms. Land use modifies the potential runoff calculated from the water balance (the typology runoff variable) to produce the actual observed runoff or discharge (e.g., V_Q), which is one of the challenges involved in relating RO and V_Q, and in the upscaling efforts discussed below. The use of population density as the primary human dimension forcing function glosses over the explanatory potential of various more refined variables (e.g., extent and types of agriculture, economic development levels, industrial and urban activities). Obviously, the scatter of points shown in Fig. 3.16 provides a basis for further analysis of those variations in terms of the influences of other factors on N and P loads to coastal ecosystems. Preliminary analyses by Sandhei (2003) have shown that agricultural land use and nutrient input variables have some potential to refine the equations, particularly for developed countries (also see Text Box 3.10). The equations derived in Fig. 3.16 provide a potential approach to generalising or upscaling some important components of coastal biogeochemical fluxes. Indeed, Smith et al. (2003) used the relationships in combination with geospatial cluster analysis to generate estimates of the global loads and their distributions. The ubiquity of human influences and the fact that they influence both of the independent variables in the load regression equations to some degree means that estimation of the pristine or natural fluxes is particularly challenging.

3.3.3.2 *Environmental Settings and Characteristics of Pristine Coastline Types*

Identification of sectors of natural (pristine, or free from major human alterations) coastline function provides the basis for:

- estimates of pre-anthropogenic fluxes for global regions and for the Earth system as a whole;
- estimates of the degree of change in material fluxes already experienced;
- making predictions about future changes, when coupled with information on the effects of human populations on fluxes; and
- understanding the natural mechanisms regulating biogeochemical cycles.

Global delivery to the ocean of DIP and DIN as a result of human activities is estimated to have increased threefold between the 1970s and 1990s (Smith et al. 2003, see Table 3.2). Earlier estimates by Meybeck (1982) were based on extrapolation by expert judgment from 30 major river basins. The global loading estimates by Smith and colleagues were derived statistically from the regression models for catchment basin loading to the ocean (see Fig. 3.16), based on the data from 165 budget sites discussed in this chapter and utilising the LOICZ typology approach. The estimated increase in human-derived DIP and DIN to the coastal ocean over the last two decades is commensurate with the dramatic increase in global population, agricultural production and atmospheric

Text Box 3.10. Anthropogenic drivers for nitrogen and phosphorus in Southeast Asia

M. L. San Diego-McGlone and V. C. Dupra

The Asia-Pacific region has a longer coastline than any other region of the world. The strategic position of these coastal areas in terms of trade and extraction of resources has resulted in a continuing expansion of the coastal human population, due to both growth and migration from inland areas. While about 50% of the world's population lives within 100 km of the coastline, and about 65% (4 billion) within 200 km of the coast, by 2025 this number should approach 6 billion, roughly today's entire world population (*http://www.prb.org/*). Southeast Asia currently has the highest percentage of coastal dwellers in the world, with some 70% (350 million) of the population living within 50 km of the coast, so human impacts within this region may foreshadow those of the global coastal zone of the future.

The massive increase in coastal population of the region, and its accompanying economic activity, has brought with it significant changes in the flux of materials from land to coastal waters. The sources of nitrogen and phosphorus may be broken down into a handful of anthropogenic activities. These activities include agriculture, human waste disposal and aquaculture. Their importance for some situations in Southeast Asia is reviewed below.

Agricultural activities, including crop and livestock production, are a primary source of nutrients to the coastal zone. Crop production contributes to N and P effluents primarily through the transport of sediments. Intensive agriculture involves significant soil erosion, and eventual sediment transport to coastal waters. Two-thirds of the world's sediment transport to oceans is in Southeast Asia (GEMS 1996). This may be due to active tectonics, heavy rainfall, steep slopes and disturbed soils that are easily eroded. Levels of suspended solids in Asian rivers have almost quadrupled since the late 1970s (ADB 1997, GEMS 1996). This problem of soil erosion is exacerbated by the increasing use of fertilisers; for the Asia-Pacific region, fertiliser consumption increased 340% from 1975–95 (ADB 1997). Livestock production also contributes to N and P effluents through the production of animal wastes. A portion of animal wastes is applied to fields as fertiliser, and finds its way to coastal waters through transport of sediments and dissolved nutrients in streamflow. The substantial portion of animal wastes not used as fertiliser may be simply flushed away to nearby water sources, making its way to coastal waters.

Human waste (sewage and solid waste) is a leading contributor to nitrogen and phosphorus effluents entering coastal waters. The growth in human waste production mirrors the growth in population and improvements in nutrition. Waste residuals will continue to be a growing problem, as most Southeast Asian countries have inadequate treatment facilities. In South and Southeast Asia, only 10% of sewage is treated (ADB 1997). Currently, only 3% of Metro-Manila (Philippines) households are connected to a central sewer that discharges directly to Manila Bay and, as of 1998, no major coastal city in Indonesia had a sewage treatment facility in place.

Coastal aquaculture takes two primary forms. Fishponds are built along coastal lands, often replacing mangrove systems that are important for their residual assimilation capacity. After harvest, fishpond waters are typically flushed directly into adjoining coastal waters. Fish pens and fish cages are located directly within coastal waters; feeds and wastes are deposited directly into the water. The introduction of excessive nutrients to coastal waters is reflected in the frequent occurrence of red tide algal blooms and fish kills along the coasts of many countries.

The impact of anthropogenic activities on coastal waters is seen not only in increased nutrient discharges but also in reduced assimilation capacity of the systems below natural levels. For example, in Southeast Asia, mangroves (documented as natural filters and sediment traps) have been reduced to about 45% of the estimated cover of the early 1900s (Talaue-McManus 2000). At present rates, the region will lose its mangrove forests by about 2030 (Talaue-McManus 2000). With less assimilation and added discharges from aquaculture ponds converted from mangrove swamps, anthropogenic impact to receiving waters has increased substantially.

The responses to nutrient loading in coastal waters were examined in 30 coastal ecosystems in Southeast Asia, particularly in China, Indonesia, Malaysia, Philippines, Taiwan, Thailand and Vietnam. In one study (Case A, below), the contribution of major economic activities to DIP and DIN load was quantified and assimilation capacity compared in four coastal bays located in Vietnam, Thailand, Philippines and Malaysia (Talaue-McManus et al. 2001). In another study (Case B, below), the physical attributes of 30 coastal bays in all seven Southeast Asian countries were correlated with DIN and DIP loads to derive possible proxies for DIN and DIP loads, useful when site data are not available (Dupra 2003). The contribution of the rivers, ocean and other sources (groundwater, atmosphere, sewage) to the nutrient (DIN and DIP) loading were discriminated for the 30 coastal sites in a third study (Case C, below, Dupra 2003).

- *Case A.* Four coastal watersheds in Southeast Asia were examined: the Red River Delta in Vietnam (mangrove-dominated), Bandon Bay in Thailand (mangrove-dominated), Lingayen Gulf in the Philippines (extensive reef system), and Merbok Estuary in Malaysia (mangrove-dominated). Agriculture contributed 20–80% of the total DIN (21% for Bandon Bay, 37% for Merbok Estuary, 64% for Lingayen Gulf, 77% for Red River Delta) and 20–80% of the total DIP (21% for Bandon Bay, 45% for Merbok Bay and Lingayen Gulf, 76% for Red River Delta) from the watershed. Household waste provided 15% of the total DIN and DIP to Bandon Bay and 33% of the total DIN and 52% of the total DIP to Lingayen Gulf. To assess assimilation in these bays, an index ratio was estimated between generated nutrient waste and total nutrient loading (Talaue-McManus et al. 2001) to compare anthropogenic influence on nutrient (DIN and DIP) loading. An index of 1 indicates highest anthropogenic impact to receiving waters, >1 implies high assimilative capacity, and <1 high loading and high impact from natural sources. The Red River Delta showed highest buffering capacity followed by the Merbok Estuary. Lingayen Gulf received the most impact from human-generated waste, while Bandon Bay was the least impacted.
- *Case B.* Among the physical attributes of the 30 coastal ecosystems, the variables that correlate well with DIN and DIP river loading are river discharge ($r^2 = 0.85$ for DIN load and $r^2 = 0.97$ for DIP load), catchment population ($r^2 = 0.85$ for DIN load and $r^2 = 0.77$ for DIP load) and catchment area ($r^2 = 0.72$ for DIN load and $r^2 = 0.49$ for DIP load). Simple and multiple regression equations that describe DIN and DIP loading in the 30 coastal ecosystems as functions of river runoff and/or population in the catchment are presented in Table TB3.10.1. The regression equations imply that log-transformed DIN and DIP river loads per square kilometer of catchment area increase with log-transformed river runoff per square kilometer of catchment area and population density in the catchment. The derived regression models may then be used to estimate DIP and DIN river loads for a coastal bay given a value for river discharge and population density in the catchment.
- *Case C.* Estimated DIN and DIP fluxes that include river load, net oceanic flux and other fluxes (i.e., sewage, groundwater flux and atmospheric flux combined) in the 30 coastal ecosystems within Southeast Asia were evaluated to determine their relative contributions to net coastal ecosystem nutrient flux. River load and net oceanic flux dominated in most of the coastal ecosystems. Net oceanic flux is generally net transport to the adjacent ocean except for coastal ecosystems with high levels of DIN and DIP waters from the outside. Net export fluxes to the adjacent ocean were influenced by the catchments draining into them and may also be parameterised by runoff and population density in the catchment.

◀

Table TB3.10.1. Regression equations for log-transformed nutrient river loads (log [F_{DINQ}/A_B] and log [F_{DIPQ}/A_B]) versus log predicting variables (log [V_Q/A_B] and log [N/A_B]). (F_{DINQ} = DIN river flux and F_{DIPQ} = DIP river flux, A_B = basin area, V_Q = run-off, N = population)

Response variable	Regression equations	Number of sites	r^2
River load			
Log (F_{DINQ}/A_B)	3.64 + 0.29 log (N/A_B) + 0.66 log (VQ/A_B)	24	0.71
Log (F_{DINQ}/A_B)	2.83 + 0.62 log (N/A_B)	25	0.39
Log (F_{DINQ}/A_B)	4.38 + 0.81 log (VQ/A_B)	28	0.65
Log (F_{DIPQ}/A_B)	2.41 + 0.24 log (N/A_B) + 0.75 log (VQ/A_B)	24	0.80
Log (F_{DIPQ}/A_B)	1.31 + 0.62 log (N/A_B)	25	0.39
Log (F_{DIPQ}/A_B)	3.16 + 0.87 log (VQ/A_B)	28	0.76

Table 3.2. Nutrient loading. Global transport of DIP and DIN in the coastal zone, estimated from 1970s data (Meybeck 1982) and 1990s data (Smith et al. 2003)

	DIP load (10^9 mol yr^{-1})	DIN load (10^9 mol yr^{-1})
1970s data		
Natural or pristine load	13	320
Global load (natural + anthropogenic)	26	480
1990s data		
Natural or pristine load	21	400
Global load (natural + anthropogenic)	74	1 350

emissions noted elsewhere (WRI 2000). Despite the differences in datasets and extrapolation methods, each assessment arrived at similar values for natural loads of DIP and DIN to the global ocean. These natural load values are indicative of the order of magnitude for loading under pristine settings. To go beyond this kind of order-of-magnitude estimate, more data and more sophisticated analyses will be required.

Since we view the unaltered past from the perspective of a substantially altered present, we are unlikely ever to be confident that we have acquired data for a truly pristine condition. However, we can certainly identify areas of relatively minimal impact and we can rank different environments in terms of their probable degree of alteration. That at least permits us to narrow the possible range of pristine values and to focus our search on the most promising or representative candidates. We discuss this subject further in Sect. 3.4.

For the preliminary assessment presented here, we assume that the degree of anthropogenic alteration of land-based inputs to the coastal zone (see Text Box 3.11) is generally substantially greater than the alteration of the oceanic fluxes. To identify relatively natural systems, we begin therefore by deciding which terrestrial areas to disqualify. In the preceding section we discussed the dependence of DIN and DIP loads on population density (clearly indicative of alteration) and runoff. The runoff is a vector for both natural and human-modified fluxes, and further, is itself subject to human alteration of surface water hydrology. In order to arrive at some degree of separation of the relative effects of runoff and population, we can classify the dataset according to value ranges for both variables. Because most of the numerical values of runoff/area and population density fall within a four order of magnitude range, and because the load relationship is defined on the basis of $\log_{10}$ variables, categorisation of the terrestrial systems into four classes based on log values is a convenient and reasonable starting point.

3.3.4 Budget Sites as Representatives of the Global System

Text Box 3.12 illustrates the basis for the four-class log-scale classification system. We use that as a starting point from which to consider the global distribution of the nutrient loads and the factors controlling them, as well as how adequately the present distribution of budget sites samples the various environments. After identifying the most critical types of coastal systems to sample and understand, we turn to the question of relating the local, budget-site measurements and data to the similar but not identical global datasets that must be used for extrapolating or upscaling the local results.

3.3.4.1 *Global System and Budget Site Distributions*

Smith et al. (2003) used data from the budget sites and the catchment basins associated with them to derive a rela-

Text Box 3.11. Inorganic nutrient fluxes in the coastal ecosystems of Southeast Asia

V. C. Dupra and M. L. San Diego-McGlone

Dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) annual fluxes have been estimated for 30 coastal ecosystems in the Southeast Asia region using the mass balance approach developed by LOICZ (Dupra et al. 2000a, 2000b). Inorganic nutrients are delivered mainly by rivers in most of the coastal ecosystems. River load and net oceanic flux generally dominate nutrient fluxes and net oceanic flux is usually net export to the adjacent ocean. River load and net export to the adjacent ocean were balanced to determine net coastal ecosystem nutrient fluxes. The net coastal ecosystem DIN and DIP fluxes are potential net biological reactive nutrients (non-conservative fluxes) and may be interpreted stoichiometrically as apparent net ecosystem metabolism.

River DIN and DIP loads may be scaled as total load per year (aggregate of loads from the catchment) or as load per square kilometer of catchment per year (called yields). Figure TB3.11.1 presents log-transformed total loads for 30 coastal ecosystems (from Dupra 2003). The coastal ecosystems that have the highest total DIN loads are Pearl (China), Madaomen (China), Aimen (China), Tien (Vietnam) and Hau (Vietnam). The biggest watersheds drain into these ecosystems. Their DIN loads (antilog of the values in Fig. TB3.11.1) vary from about 2×10^9 moles yr^{-1} to 6×10^9 moles yr^{-1}. The other coastal systems received relatively smaller total DIN loads. Total DIP loads were highest for the Pearl, Hau and Tien rivers. Their loads fall between about 0.2×10^9 moles yr^{-1} and 0.4×10^9 moles yr^{-1}. Total DIP loads for Modaomen and Aimen are not elevated in proportion with DIN. Lingayen Gulf (Philippines) and Manila Bay (Philippines) have comparable DIP loads with Madaomen and Aimen, respectively. The other coastal systems have relatively low DIP river loads.

Figure TB3.11.2 illustrates log-transformed river nutrient loads scaled by catchment (load per square kilometer of catchment area per year) (from Dupra 2003). Hau (Vietnam) and Tanshui (Taiwan) have the highest DIN load per square kilometer. These systems have small catchment areas. The other coastal systems have < 100 kmol km^{-2} yr^{-1} DIN load. The Philippine systems (Sogod,

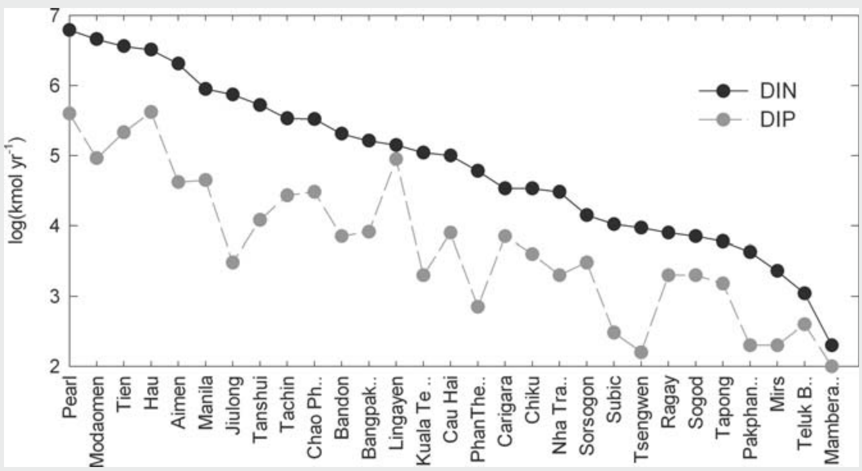


Fig. TB3.11.1. Log transformed dissolved inorganic nitrogen river load (F_{DINQ}) and dissolved inorganic phosphorus river load (F_{DIPQ}) for the coastal ecosystems in the Southeast Asia region. VanPhong Bay river load is 0 (log is undefined) and is excluded in the analysis

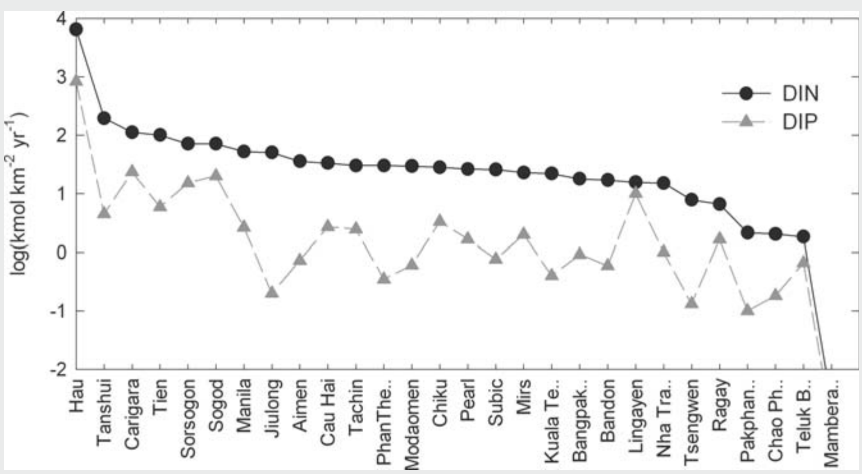


Fig. TB3.11.2. Dissolved inorganic nitrogen river load per catchment area (F_{DINQ}/A_B) and dissolved inorganic phosphorus river load per catchment area (F_{DIPQ}/A_B) for the coastal ecosystems in the Southeast Asia region. VanPhong Bay has 0 nutrient river load and Tapong Bay has 0 catchment area (log is undefined) and are excluded from the analysis

tionship between the yields of DIP and DIN and the area-normalised runoff and populations of the catchment basins. They then used geospatial clustering techniques to develop an estimate of the global coastal DIP and DIN loads, based on the distributions of the independent variables.

We assume that regardless of the uncertainties in the Smith et al. (2003) regression equations, the relationships are sufficiently representative of the processes and relationship to provide guidance about the relative importance of various factors and geographic regions to the

◀

Carigara, Sorsogon and Lingayen) have the highest DIP load per square kilometer (> 10); the other coastal systems have less than 5 kmol $km^{-2} yr^{-1}$ DIP loads.

Negative net oceanic DIN and DIP fluxes in the budgeted coastal ecosystems represent net exports of nutrients from the system to the adjacent ocean. Budgeted coastal ecosystems with negative net oceanic nutrient flux were grouped and analyzed to determine relationships between net oceanic fluxes and river loads. Relationships of log-transformed river loads and net oceanic fluxes for both DIN and DIP are presented in Fig. TB3.11.3 as scatter plots (from Dupra 2003). The negative (i.e., outward) net oceanic fluxes were changed to positive before logarithmic transformation of the data. For both DIN and DIP fluxes, net oceanic flux is highly coupled to river load, $r^2 = 0.87$ and 0.81, respectively. The slopes of both lines differ considerably from 1. It seems that for both DIN and DIP, there is increasing export of the nutrients to the adjacent ocean with increase in river nutrient loads and the increase in the nutrient export is proportionally lower than the increase in nutrient load. For DIN flux, solution of the regression equation indicates that an increase of DIN river load from 1×10^6 mol yr^{-1} to 10×10^6 mol yr^{-1} would mean an increase of net oceanic export of DIN from 2×10^6 mol yr^{-1} to 18×10^6 mol yr^{-1}. In the case of DIP flux, changing river DIP load from 0.1×10^6 mol yr^{-1} to 1×10^6 mol yr^{-1} would result in an equivalent change in net oceanic export from 0.2×10^6 mol yr^{-1} to 1.8×10^6 mol yr^{-1}. Net oceanic flux to the adjacent ocean was approximately twice as much as the nutrient river load. Seemingly the dissolved inorganic nutrients from the river support only half of what is being transported to the ocean. However, the strong relationships between the river load and net oceanic export suggest that either the river would support an internal source of the net oceanic export or the river flux carries organic materials that are oxidised to release the required dissolved inorganic nutrients within the estuary.

River nutrient loads and net export oceanic flux in log DIN $km^{-2} yr^{-1}$ and log DIN $km^{-2} yr^{-1}$ for the 30 coastal ecosystems may be described as linear functions of runoff per square kilometer of catchment per year and catchment population density. The regression equations that describe river nutrient loadings in the 30 coastal ecosystems may be applied to the coastline of the Southeast Asia region using regional data on runoff and population density in the catchment to derive patterns of nutrient loading.

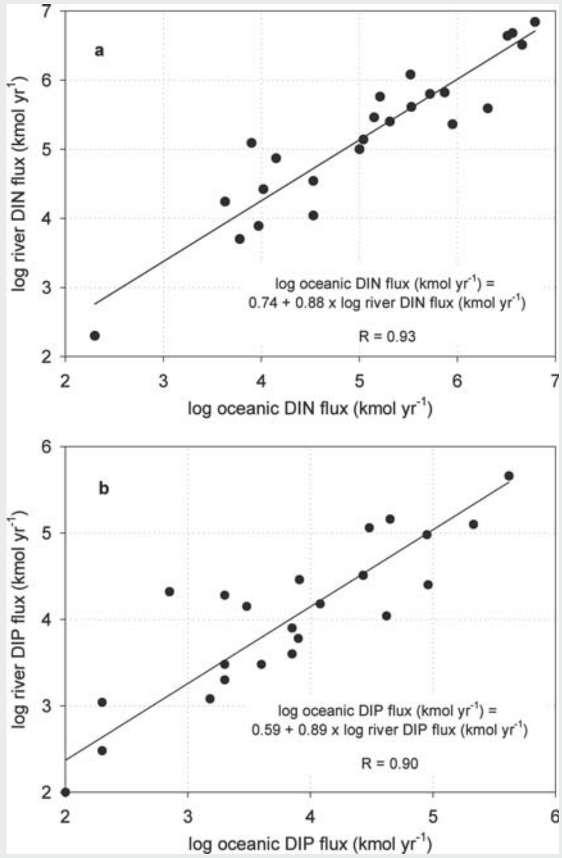


Fig. TB3.11.3. Scatter plots of log-log nutrient river load (F_{DIPQ}) versus net oceanic flux (F_{DIPOcn}) for Southeast Asia budgeted coastal ecosystems with net export (from the system to the adjacent ocean) oceanic nutrient flux. The convention of negative sign for net export in the budgets was reversed for log transformation

magnitudes and distributions of coastal biogeochemical fluxes. Independent variables and basin area can both be conveniently classified into four order-of-magnitude classes (see Text Box 3.13). For initial analysis we have employed a four-by-four matrix with log runoff/area classes of < −2, −2 to −1, −1 to 0, and > 0 and with log population density classes of < 0, 0 to 1, 1 to 2 and > 2.

Because the form and coefficients of the DIN and DIP regression equations derived by Smith et al. (2003) are very similar, there are no significant differences between the relative distributions of the two nutrients, and in this discussion we simply average the DIN and DIP results and present total nutrient load. Applying the equations to the global runoff, area and population data from the LOICZ database, we obtain the normalised yield and calculated distribution of the loads (Fig. 3.17).

The normalised yield, which is positively correlated with both variables, predictably shows a smooth increase from low to high values on both axes. The realised load, however, is primarily a function of the area of land within each class, and secondarily a function of the details of the normalised runoff and population values within the classes. The distribution of the total nutrient load therefore differs strikingly from the yield distributions, as seen in Fig. 3.17b and the associated table.

Two of the matrix cells account for 61% of the global load, another two for an additional 23%, four more add an additional 14%, while the other half of the 16 matrix cells contribute only a few percent. Over 90% of the total load comes from the six cells formed by the intersection of the two highest runoff classes and the three highest population density classes. The uncoloured and unshaded numbers in the table of Fig. 3.17 identify the locations that seem most likely to provide natural background (pristine) load values relevant to the enhanced loads derived from the higher population locations in the same runoff categories.

Text Box 3.12. Classification of river basins and budget site nutrient loads

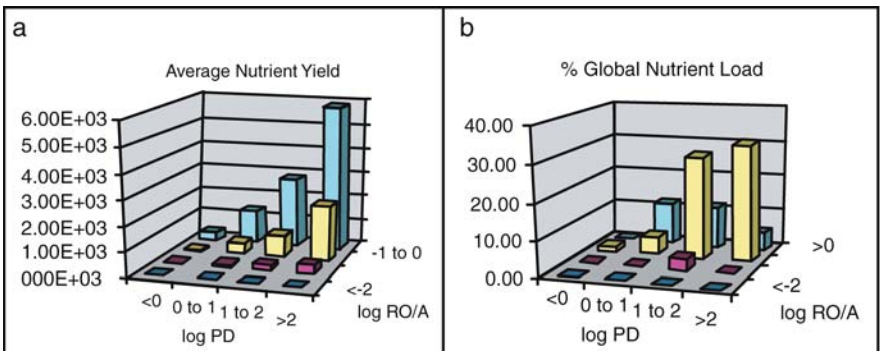
R. W. Buddemeier and S. V. Smith

How well do the LOICZ budget sites represent, or sample, the river basins of the world coastal zone? To answer that question with respect to the size distribution of the basins, we considered 8 016 typology database coastal cells contained within the global 60° S – 66° N latitude band. We compared these with budget site datasets based on both the typology database values and the values derived from the kilometer-scale basin analysis. The exclusion of the high latitude cells was based on the fact that very few budgets are within this latitudinal range, and on the considerations given in Text Box 1.7, Chap. 1.

Of the basins for which budget-sites are available, 30% have no corresponding half-degree sub-basin area in the typology database; this means that they have land areas too small to have been resolved by the University of New Hampshire flow model that generated the sub-basin areas. For this analysis these basins were assigned the land area of the typology cell in which they occur. This generates a typology basin area dataset with values that overestimate the actual basin areas substantially, but that are of the correct order of magnitude for the log-scale distribution analyses presented below.

Figure TB3.12.1 illustrates the distributions of areas and the critical population density and runoff/area variables across log-scaled size classes for the global database and both the typology and km-scale datasets for the budget site basins. Of the global coastal cells, 85% contain half-degree basins with area < 10 000 km^2. Many of these reflect the assigned cell area (2 000–2 500 km^2) rather than a true basin area; this underestimates the actual number of small basins, since cells may contain more than one basin and discharge point. For the half-degree budget basin dataset the corresponding percentage is ~45, but when the km-scale basin areas are used, this percentage rises to ~55. The current LOICZ collection of budgets therefore over-samples the larger area basins and under-samples the smallest coastal systems. Similar patterns are observed in the cases of population density and runoff/area, but here the general distribution patterns (summarised by the shape of the cumulative percentage plot) are reasonably similar. Most of the classes of budget site values have enough members to support at least rudimentary within-group statistical analysis.

From the standpoint of estimating global loads, the distribution of the budget basins is reasonable, since the higher values of both population density and runoff are likely to dominate the total fluxes. However, for evaluating pristine fluxes, the distributions are poor – the lowest values of population density, which are seriously under-sampled, are most likely to provide access to a near-natural signal. These observations do not determine or address the issues of terrestrial forcing directly. Consideration of basin size will probably be a critical factor in regional flux determinations, since for sub-global determinations the coastal zone dominance by small systems will have to be explicitly considered. Given the resolution limits imposed by the half-degree data system and differences between the typology and km-scale datasets, these distributions help set the stage for defining the types of variables that can be used, and systems and issues that may be successfully addressed, by upscaling on the basis of basin-level characteristics.



c

logRO/logPD	<0	0 to 1	1 to 2	>2
>0	0.3	11.8	11.1	5.2
-1 to 0	1.4	5.1	28.7	31.8
-2 to -1	0.1	0.3	3.3	0.8
<-2	0	0	0.1	0

Fig. 3.17. Nutrient loading. Global distribution of nutrient yields (**a**, *left*) and loads (**b**, *right*) calculated using 7 016 coastal basin cells between 60° S and 66° N, the typology dataset, and the regression equations derived by Smith et al. (2003). Note that table cells are oriented to correspond to cells in the bar chart if the chart base were raised to the vertical. *Grey background* indicates negligible contribution to the global load, and the *unshaded cells* are those with high potential for identifying natural background (pristine) fluxes. Other *cell colours* are indexed to the colours in the bar charts above the table

Figure 3.18 compares the distributions of land area, approximate catchment number, runoff/area (RO/*A*), and population density in the 4 × 4 matrix, and also plots the distribution of the present inventory of budget sites on the same basis. This provides a basis for evaluating both the utility of the present dataset and the needs for additional data. The first pair of plots contrasts the total land area (including the inland drainage basins that discharge through the coastal cells) associated with the coastal typology cells in each of the 16 classes. One unit accounts for about 25% of the total land area, but when the numbers of systems (coastal typology cells or, very approximately, coastal catchments) is considered, the distribution is much more even. This is a graphic illustration of the fact that most budgeted coastal systems are relatively small in total area. We believe that small ecosystems numerically dominate the world coastline.

The second pair of plots illustrates the distribution of the totals of runoff and population. Runoff follows the pattern of area across the RO/*A* gradient. The population plot points up the human dimension impact – one matrix unit with only about 10% of the land area con-

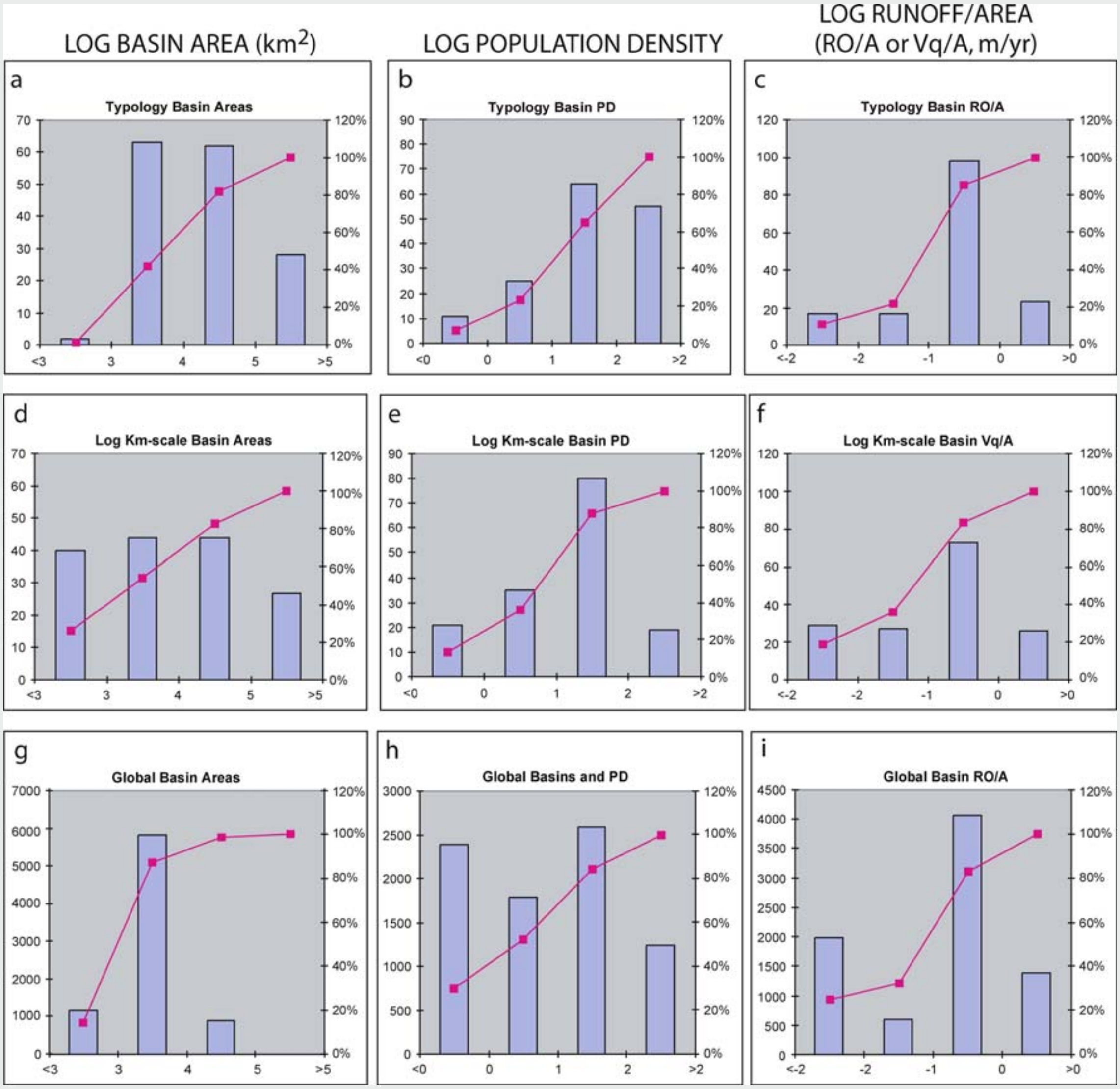


Fig. TB3.12.1. Frequency distributions of $\log_{10}$ values of three drainage basin variables (area, km^2, *left column*; population density, people km^{-2}, *center column*; runoff discharge, $m\,yr^{-1}$, *right column*). *Left axes* (*bars*) are numbers of basins; *right axes* (*line and dots*) are percent of total sample. Panels **g**, **h** and **i** (Global Basin) depict the distribution of the typology database values in 8016 coastal cells between 60°S and 66°N. Panels **a**, **b** and **c** (Typology Basin) display the distributions of the same variables as sampled by 155 LOICZ biogeochemical budget sites, and the panels **d**, **e** and **f** (Km-scale Basins) display the corresponding distributions determined by use of the refined basin areas and the budget surface water discharge data. Note that the relative proportions of the two lowest classes of basin area are distorted in the typology displays by the 0.5° grid system, which forces an area cut-off in the 10^3–10^4 km^2 region. There are almost certainly more basins in the <10^3 km^2 class than in the next larger class.

tains over 50% of the population and accounts for 30% of the total load (as shown in Fig. 3.17). The final pair of charts in Fig. 3.18 shows the distributions of the LOICZ budget sites among the matrix units using two different calculation methods. Figure 3.18e uses the same typology values used in the global descriptions to classify the sites, whereas Fig. 3.18f is calculated on the basis of the budget V_Q/A values and areas determined for the km-scale basins.

Overall, comparison of either Figs. 3.18e or 3.18f with Fig. 3.17 suggests reasonably good representation of the two highest load classes, and at least some sampling of most of the other categories. This is admittedly a somewhat circular argument, since the load predictions were

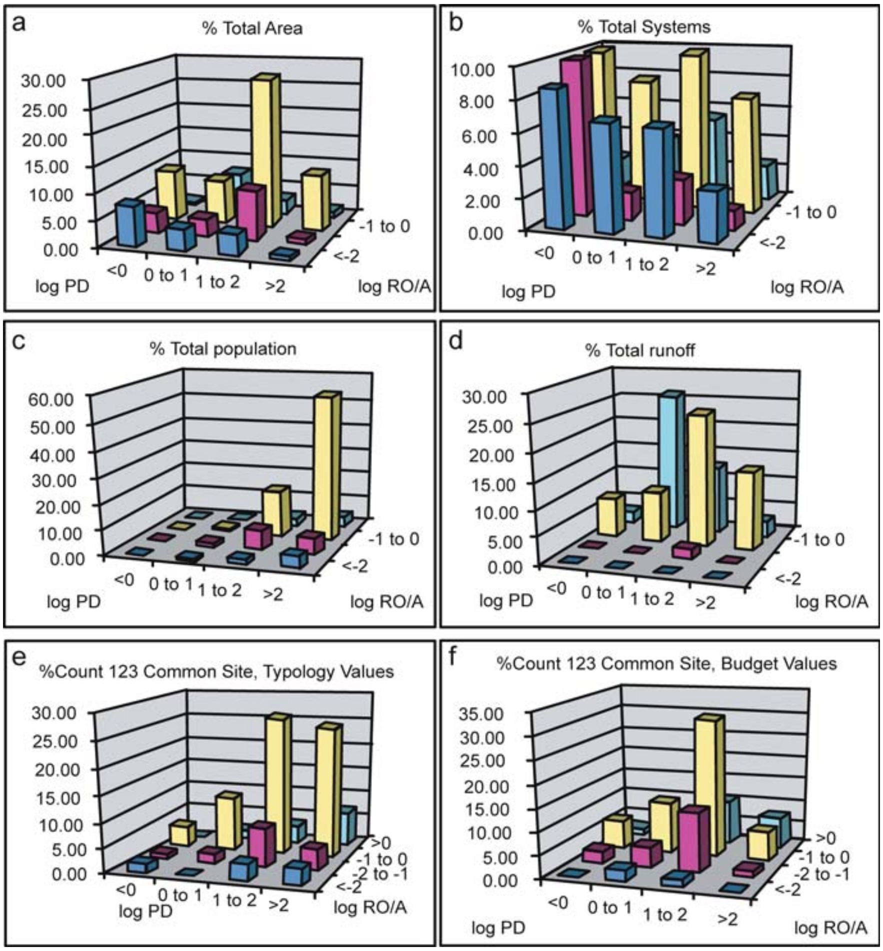


Fig. 3.18. River basin runoff. Global 16-class distributions based on population density and runoff/area of coastal basin: **a** land area; **b** number of coastal cells/basins; **c** percentage of total population; **d** percentage of total runoff; **e** percentage of budget basins calculated with typology database values; **f** percentage of budget basins calculated with budget dataset variable values

derived from the budget distribution shown, but as the discussion by Smith et al. (2003) points out, the results are consistent with other estimates and models, and we have not found the scatter of the data points in Fig. 3.16 to be strongly related to the load values.

These initial classifications of the coastal zone in terms of delivered DIN and DIP have implications for both the interpretation of the results and the extension of the research. One important point is only indirectly illustrated here (see the comparison of system number and total area above) – the disparity between the dominance of larger systems in determining total load delivered to the ocean, and the dominance of smaller systems in characterising the largest proportion of the coastline. This is illustrated graphically in Chap. 5. The previous sections of this chapter have emphasised the variety of influences on how delivered load is actually processed within the coastal zone and the importance of the small-system, inner-shelf processes in overall coastal biogeochemical fluxes. Because of this, and because coastal processes are important locally apart from their contribution to the global budgets, the load distributions illustrated in Fig. 3.17 are not the only factors determining the significance of coastal systems.

Another issue is the question of baseline fluxes, or the pristine loads without human effects. Although areas with high and growing loads might reasonably have some priority for further study, predicting and mitigating changes due to increasing population and development requires some understanding of pre-impact conditions. In order to achieve this, greater attention to low population density analogues of the high-population, high-load regions is required. Text Box 3.13 illustrates some of the differences to be expected between pristine and perturbed sites. It also illustrates the confounding effects of runoff; since humans are terrestrial animals, the absence of terrestrial runoff will tend to shield coastal waters from human impacts. However, arid or strongly ocean-dominated sites are unlikely to produce baseline data from which we can deduce the pristine characteristics of wet but unaltered locations.

Finally, this initial classification approach leads to two conclusions that deserve emphasis:

1. Reconsideration and more detailed analysis of the initial order-of-magnitude classifications is in order. The high load, large area, high population regions deserve a more finely resolved analysis, as do the re-

Text Box 3.13. Perturbed and "pristine" systems

V. Camacho-Ibar and R. W. Buddemeier

Most LOICZ budgets developed within the Latin American region correspond to sites with some degree of anthropogenic impact, and this is particularly the case of systems associated with permanent rivers. This probably reflects both that few coastal ecosystems in this region remain unaffected by human activity, and that the scientific community in the region has focused its studies on local, accessible systems rather than on remote systems difficult to access (both in terms of logistics and the cost of sampling). These inaccessible sites are precisely the systems likely to be least subject to anthropogenic influence, such as some remote coastal lagoons in the arid region of NW Mexico (Gulf of California), which are as yet under negligible human pressure.

For this comparison, we contrast two "perturbed systems," Maricá-Guarapiná (MG), Brazil and Cienega Grande de Santa Marta (CGSM), Colombia, with Bahía San Luis Gonzaga (SLG), Baja California, Mexico which is a system with essentially no human impact.

Maricá-Guarapiná and Cienega Grande de Santa Marta represent qualitatively different types of perturbations. MG is heavily loaded with sewage and has undergone some hydrologic modification, while CGSM suffers primarily from severe alterations of its hydrologic regime by road construction, water diversion and other forms of development that have altered its ecosystem components.

The Maricá-Guarapina (MG) system (Couto et al. 2000, *http://data.ecology.su.se/MNODE/South%20America/MG/mgpi.htm*) comprises three small choked coastal lagoons and a wetland connected by narrow channels, on the east coast of Rio de Janeiro state. Present anthropogenic influence is mainly sewage inputs, but in the 1950s the system suffered several hydrologic impacts including artificial change of the oceanic opening from the middle to the eastern extreme, and since then landfill in the link channels has restricted water circulation.

The Cienaga Grande de Santa Marta (CGSM) system (Rivera-Monroy et al. 2002, h*ttp://data.ecology.su.se/MNODE/South%20America/cienegagrande/cienagagrande.htm*) is a lagoon-delta ecosystem that forms the exterior delta of the Magdalena River, the largest river in Colombia. This system can be classified as a type I setting (river-dominated, arid, with low tidal amplitude) containing fringe, basin and riverine mangroves (Thom 1982). The CGSM has been impacted by the construction of a coastal highway and a road levee along the Magdalena River. The resulting alteration of the natural flow of marine and freshwaters in combination with freshwater diversion has caused hypersalinisation of mangrove soils leading to die-off of almost 27 000 ha of mangrove forest in a 36-year period (Botero 1990, Cardona and Botero 1998). In 1993, a rehabilitation project was initiated to re-establish the hydrology in some areas of the CGSM and restore both the hydrologic regime and the mangrove forests (Twilley et al. 1999).

The Bahía San Luis Gonzaga (SLG) system (Delgadillo-Hinojosa and Segovia Zavala 1997, *http://data.ecology.su.se/MNODE/mexicanlagoons/slg.htm*) in Baja California is a small, rapidly exchanging bay covering an area of about 3 km^2 in an arid region. In addition to low annual rainfall ($P < 4$ mm; $E \gg P$), population in the drainage basin is very low (~30 people) and scattered, with no significant industry, agriculture or sewage discharge. It is naturally productive (GPP 130–190 mmol C m^{-2} d^{-1}) but is net heterotrophic on an annual basis. Table TB3.13.1 summarizes some of the important characteristics of the three systems.

The characteristics of the three systems are consistent with the general coastal characteristics discussed in Sect. 3.4. and in the sections dealing with marine, terrestrial and human dominance. The arguably pristine system in this case is strongly ocean-dominated, having neither significant terrestrial nor human inputs, and is net heterotrophic. The more perturbed systems have shifted toward autotrophy, apparently as a result of reducing ocean exchange via physical alteration of channels and (in the case of MG) greatly increasing nutrient loads.

These observations further reflect the messages of Figs. 3.18 and 3.21 – there are many candidate pristine sites on the numerous arid coastlines of the world, but these generally are dominated by ocean forcing, and will only weakly represent the salient differences between inner coast and shelf or ocean metabolisms. More important for assessment purposes is the identification of relatively unperturbed systems with a substantial amount of terrestrial – but not human – influence; these types of system represent coastal input to the global cycles characteristic of predevelopment conditions, and in which the human-driven changes have been and will continue to be the greatest.

Table TB3.13.1 Comparison of perturbed and unperturbed Latin American coastal systems. Systems included: Marica Guarapini, Brazil (MG), Cienaga Grande de Santa Maria, Colombia (CGSM), Bahia San Luis Gonzaga, Baja California, Mexico (SLG)

	Perturbed		Unperturbed
System	**MG**	**CGSM**	**SLG**
Stresses	Sewage loading, hydrologic modification	Hydrologic modification	none
Responses	Eutrophication	Ecosystem loss (mangrove die-off)	–
Vq (10^6 m^3 yr^{-1})	~95	100	0
Forcing	Runoff and nutrient load	Runoff/exchange	Exchange/upwelling
ΔDIP (1 000 mol yr^{-1})	–610	Slightly negative	Intra/interannually variable
ΔDIN (1 000 mol yr^{-1})	–6	Slightly negative	Intra/interannually variable
[*nfix* – *denit*] (mmol N m^{-2} d^{-1})	0.28	0.4	Seasonally +/–
[*p* – *r*] (mmol C m^{-2} d^{-1})	1.8	2	Seasonally +/–
NEM	Autotrophic	Autotrophic	heterotrophic

gions in which runoff is the major contributor to load. All of the significant sub-categories will need to be examined in terms of climatic and socio-economic factors for the next stages of classification and analysis. Some of the initial considerations are illustrated in the discussion of future loads in Sect. 3.3.6, but further data will be required for these efforts. However, the initial LOICZ studies have developed the targeting mechanisms and rationales to make further work more efficient and informative.

2. The disparities between the budget variable values and the comparable typology datasets (illustrated in Figs. 3.18e and 3.18f) need to be resolved. Ultimately, upscaling must be based on regionally or globally available datasets. However, to date, the successful development of relationships (Fig. 3.16) has been based on the biogeochemical budget variables. The following section presents a more detailed comparison of the two categories of variables for the budget sites.

3.3.4.2 *Comparison of Budget Variables*

An obvious potential problem in scaling is the breakdown of quantitative correspondence between typology variables and budget-system variables for the large number of budget systems (sites and associated catchment basins) that are poorly represented by half-degree cells. Basin area provides the most straightforward demonstration of this problem, but any extensive variable (i.e., one whose value is proportional to the size of the system) will present similar problems. The basin size at which the half-degree typology basin descriptors may become a relatively poor predictor of the GIS-refined km-scale basins is shown in Fig. 3.19.

The results in Fig. 3.19 indicate that the areal correspondence breaks down in the basin area range of 1 000 to 10 000 km^2 (log = 3–4), values approximately equivalent to the area of a few low-latitude typology grid cells. This is neither subjectively unreasonable, nor particularly unexpected for a gridded typology system in which the smallest defined unit is 2 500 km^2. A value of about 3.3 on the $\log_{10}$ km-scale basin area axis (~2 000 km^2) corresponds to the area of a single typology cell. Within the typology system, the cell area is used for budget basins when no half-degree basin is identified in the database. At this value, the correspondence between half-degree and km-scale basins breaks down almost completely.

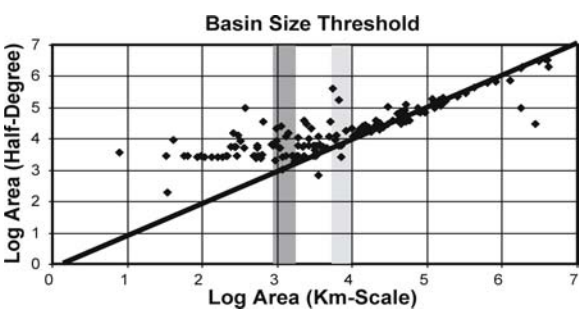


Fig. 3.19. River basin runoff. Scaling relationships of the two datasets. The log plot of the half-degree basin area against the km-scale basin area was obtained by detailed GIS analysis. The solid line is the 1 : 1 correspondence line. The two shaded lines show the region just below 10^4 km^2 where the relatively tight relationship starts to break down, and the region below about 10$^{3.3}$ km^2 (approximately the area of a single mid- and low-latitude half-degree or typology cell) where any correspondence is lost. The dataset consists of 155 reasonably localised basins with data for both typology and km-scale basin areas

However, area-normalised variables (e.g., runoff normalised to catchment area or population density) can serve as a basis for process analysis and prediction (e.g., Fig. 3.16) using some of the critical forcing variables, and they also provide a basis for upscaling that avoids the problems of extensive variables. If the small coastal basins (areas < 10 000 km^2) are generally subject to reasonably consistent *local* hydrologic forcing (i.e., on the scale of a few grid cells), area normalisation of variables that do not have steep gradients or discontinuities on that same scale should permit upscaling with little distortion of results.

For coastal cells in the typology database that contain the discharge point of a half-degree basin < 10 000 km^2 and have both basin and cell runoff values, there is no significant difference between the area-normalised runoff values for half-degree basin and the discharge-point cell. This confirms that the modelled runoff variable in the database exhibits only minor spatial variation at the scale of a few grid cells. Predictably, the km-scale basin runoff determined from the same cell-based typology runoff data also does not differ significantly from cell and half-degree basin values. The more critical question is how these globally available variables relate to the budget system variables and especially to V_Q, the river discharge.

The results of using normalised variables to compare the km-scale budget basins and the corresponding half-degree typology basins are presented in Figs. 3.20a–c for three different types of variable comparisons. Figure 3.20a compares the two normalised basin runoff estimates using different, but arguably comparable, runoff parameters – typology runoff for the half-degree basins, and V_Q for the km-scale budget basins. Figure 3.20b illustrates the effects of area-normalisation only, showing the comparison between the half-degree normalised typology runoff and the same runoff data used to calculate the value for the corresponding km-scale basin area. Figure 3.20c shows the km-scale and half-degree basin comparisons of population density based on sampling the same higher-resolution original dataset (the native LandScan population coverage used to populate the database) using both the half-degree and the km-scale basin areas.

Runoff comparisons between the two datasets (RO and V_Q) for small and large basins show large systematic differences (Fig. 3.20a), with the smaller basins data subset less well correlated than the larger basins. The slope of the regression line is such that the half-degree basin values over-predict the km-scale values for the lowest runoff basins, under-predict the highest values of V_Q, and show a noisy but reasonable relationship in the runoff range of about 0.1 to 1 m yr^{-1}. Under these circumstances, effective upscaling will probably require either a focus on the basin types that are most reliably predicted, or an improved understanding of nature and types of basins showing systematically different responses in the two variables and how these differences might be reduced or calibrated.

The data of Fig. 3.20b suggest that the problems in comparing V_Q and RO values lie primarily with the differences between the runoff variables rather than with the areal scaling. When the same runoff dataset is used for normalisation by both sets of basin areas, the resulting comparison is close to 1 : 1 overall, with good correlation coefficients. The small basins deviate from this pattern because of the influence of four very low runoff/area values that force a slope < 1; without these, the correspondence is substantially better.

In the case of the larger (> 10^4 km^2) basins, for population density (Fig. 3.20c) the correlation is very high and the relationship very close to 1 : 1. For the small basins, the correlation is not quite as good, but the slope is not substantially different. However, the half-degree basin values consistently under-predict population densities in the corresponding km-scale basins. This is understandable, since population density can vary significantly over scales of tens of kilometers, and there is probably a general tendency for populations to be higher in close proximity to streams and rivers.

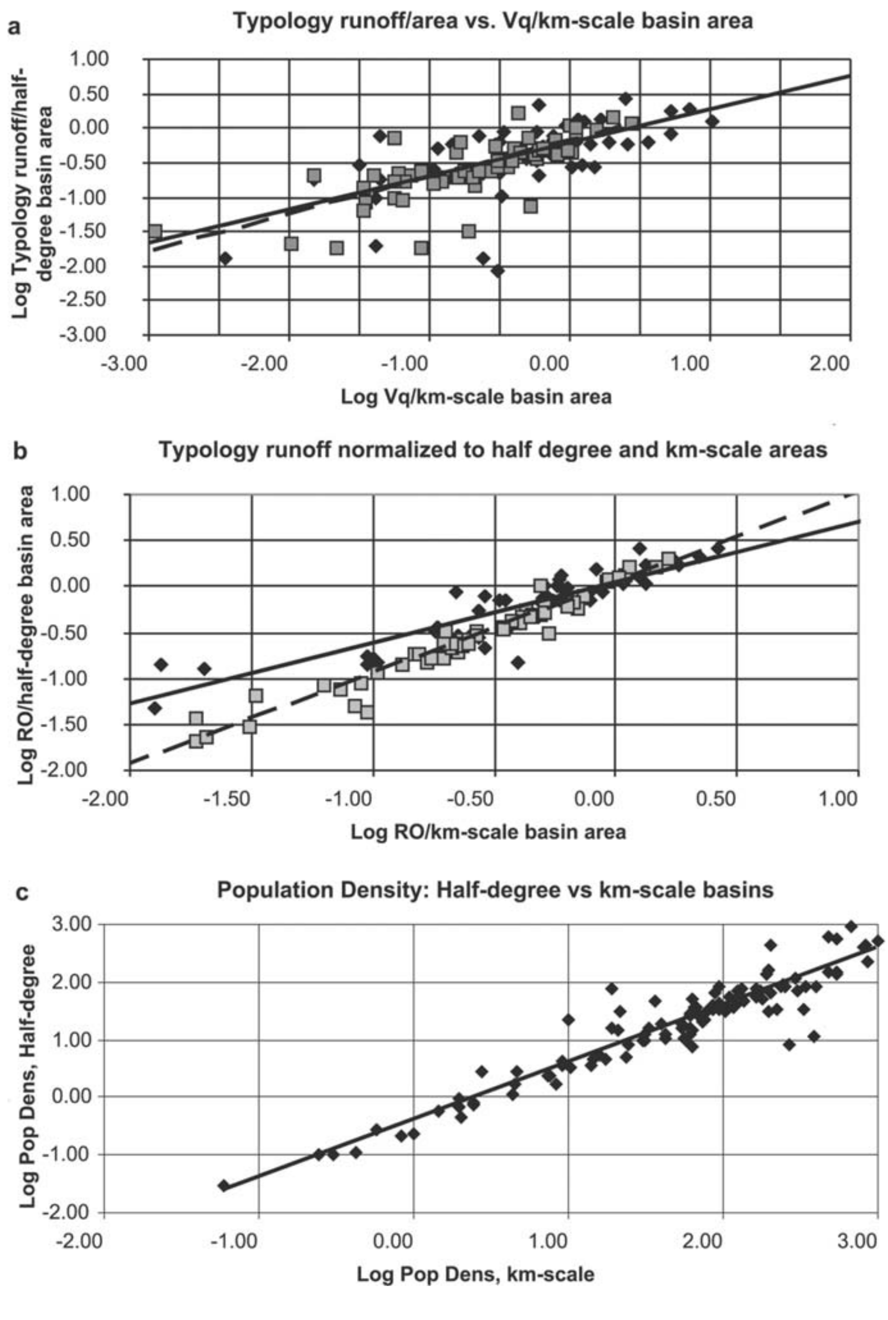


Fig. 3.20.
River basin runoff. Normalised variables comparisons.
a Comparison of area-normalised typology (half-degree) runoff and V_Q (km-scale) values. Regression for the total dataset is $y = 0.51x - 0.24$, $R^2 = 0.48$, $n = 115$. For the small basins (< 10^4 km^2; *diamonds, solid line*) the regression is $y = 0.48x - 0.25$, $R^2 = 0.40$, $n = 57$, and for the large basins (> 10^4 km^2; *squares, dashed line*) $y = 0.54x - 0.21$, $R^2 = 0.56$, $n = 58$. Basins with zero values for either runoff variable have been omitted, as have a few extreme outliers.
b Comparison of typology (half-degree) runoff values normalised to the half-degree and the km-scale basin areas. Regression for the total dataset is $y = 0.98x + 0.07$, $R^2 = 0.90$, $n = 115$. For the small basins (< 10^4 km^2; *diamonds, solid line*) the regression is $y = 0.66x + 0.02$, $R^2 = 0.80$, $n = 57$, and for the large basins (> 10^4 km^2; *squares, dashed line*) $y = 0.99x + 0.03$, $R^2 = 0.95$, $n = 58$. Discarding the values below −1.5 brings the small basin regression line very close to 1 : 1, but with a somewhat smaller correlation coefficient.
c Comparison of population density (log persons km^{-2}) of basins determined from the edited half-degree and km-scale data sets ($y = 0.99x - 0.40$, $R^2 = 0.89$, $n = 108$). The correlation is good, and no significant variations are observed if the dataset is divided into small basins (area < 10^4 km^2; $y = 1.01x - 0.38$, $R^2 = 0.84$) and large basins (area > 10^4 km^2; $y = 0.98x - 0.42$, $R^2 = 0.98$)

3.3.5 Typology for Flux Extrapolation

3.3.5.1 *Coastal Classifications as Flux Predictors*

Extrapolation of flux estimates from known sites or typical coastlines to unmeasured but similar regions is a fundamental component of the upscaling approach (see Text Box 1.6, Chap. 1). The ability to associate appropriate coastal classes with flux values is an essential step, the initial components of which are presented in Sect. 3.3.3. The project has had significant success in some areas, while the problems encountered in others have helped to identify the additional data and tools needed to fully implement the upscaling effort.

The most clear-cut success has come in the classification of river basins in terms of their probable DIP and DIN load based on globally available data (Smith et al. 2003). The correlation relationships are best if specific V_Q values for each budget site are used for runoff; global climatology runoff values can be substituted, but further work is needed to improve the correspondence and substitutability (see Fig. 3.20a). This relationship, derived over a wide range of basin sizes and types, can almost certainly be extended to basins in general and to those coastal regions not identified as part of specific catchments in global-scale elevation models.

The prediction of DIP and DIN loads can be further improved; preliminary studies have already suggested that for some regions, additional economic and land-use variables can significantly improve on the predictions developed with population density as the single proxy for human influence (Sandhei 2003). Further, the success in developing this classification system provides some assurance that effective classification schemes related to the critical non-conservative fluxes in the budget systems can be developed.

In the case of the non-conservative fluxes, it was pointed out in Sect. 3.2.3.2 that water residence time and some of the related variables are important in explaining the sign and magnitude of ΔDIP and ΔDIN, and in Sect. 3.2.3.3.2 that "… *smaller coastal systems (as opposed to large, shelf seas) are the dominant engines of coastal zone metabolism* …" Although the typology database has values for relevant variables, and the general conceptual basis for understanding controls on water residence time is well-established (see Sect. 3.3.2), efforts to develop a satisfactory regression or cluster-based classification system for these variables have so far been unsuccessful. We believe that this is a special case on the marine side of the need for finer resolution datasets noted in the catchment basin flux studies. Many of the budget systems are small compared with a half-degree cell, and these small systems may be disproportionately important in terms of their effects on overall non-conservative fluxes. Inability to resolve the oceanic forcing variables at a scale that can relate to small system function is probably one of the major challenges to be overcome in developing a full typologic approach to global flux estimates in the coastal zone.

We foresee two concurrent approaches to this problem. One is to develop better indices of coastal complexity and exchange from the existing (and steadily improving) global-scale datasets. As noted above, the bathymetry data, the coastline itself and some of the satellite-derived datasets, such as productivity and water clarity, can show features substantially smaller than a half-degree. In addition, vector representations of coastline and (for example) wind orientation could be used to substantially refine estimates of exposure and potential exchange. In addition to such complexity indices, improved estimates of cross-shelf transport and open-boundary exchange could be developed by using combinations of chemical and physical data to define gradients rather than localised values. Even if the final products are formulated at the half-degree scale, appropriate combinations of these variables as proxies for sub-gridscale features could substantially improve the dataset for application to dynamic variable prediction.

The other approach that will be needed is analogous to the development of the km-scale basin analyses. The marine equivalent of the watershed will need to be defined at a resolution that will permit more accurate association with the typology variables than is possible with the present set of observations. As with the basins assessments, we expect that Geographic Information System analysis and mapping of the systems and variable distributions will be a major step forward in linking system-level observations to generalised coastal zone characteristics. As information technology develops, it will be possible to incorporate higher resolution datasets within the coarser grid systems. This, in combination with GIS-defined budget systems, will greatly improve capabilities for examination of cross-scale relationships among the variables available for system and process characterisation and for upscaling.

3.3.6 Prospects for Future Fluxes and Their Assessment

3.3.6.1 *Climatic Controls and Geomorphic Evolution*

Climatic controls on fluxes may be assessed for both oceanic and terrestrial changes, for changes in the input fluxes (e.g., marine and terrestrial DIP and DIN) and for changes in the conditions of the coastal biogeochemical processes that influence the nature and rates of non-conservative fluxes within the system. On the marine side, changes in upwelling and wave or current strength may occur, but predictive abilities are limited and the rates of change seem relatively slow compared with the more dynamic terrestrial inputs. Changes in the physical structure of the coastal interface (e.g., erosion, sedimentation, subsidence, inundation) may affect the nature of the coastal system in significant ways. The most confidently predictable effect is a probable sea-level rise of 0.3–0.5 m by 2050 (Houghton et al. 2001). Coastal vulnerability and impact assessments have been carried out for human infrastructure and ecosystem function (e.g., Scavia et al. 2002) but the effects of sea-level rise on the overall biogeochemical functioning of the coastal zone have not yet been evaluated.

Changes in terrestrial input can be viewed in terms of the DIP and DIN load dependence on population density and runoff, discussed above. Runoff may be influenced by climate change through both precipitation and land cover, but both land cover and the hydrologic cycle (especially runoff) are subject to greater modification by humans in areas of significant population. Figure 3.17a shows that the DIP and DIN loads are relatively less sensitive to runoff than to population; the left hand row of bars (PD, population density, < 0) rises much more slowly with increasing runoff than the two higher runoff categories (toward the rear of the plot) rise with increasing population effects. Overall, the most probable short-term drivers of changes in coastal zone fluxes are human alterations of the environment (see also Text Box 3.11).

3.3.6.2 *Human-induced Change: Where and How Fast*

Humans may change coastal zone fluxes in many ways, including land-use changes, interception of runoff for consumption, waste disposal or contamination and direct actions to modify coastlines and nearshore morphology. At local and regional scales these effects are likely to outweigh the influence of climate change, with global-scale effects that are readily predictable. At present, our best predictive tool relies on the general correlations between yields, population density, runoff and the resulting loads.

Figure 3.21 brings together the geographic distributions of the $\log_{10}$ population density and runoff classifications discussed above with a clustered map of $\log_{10}$ nutrient yield for the small coastal basins (represented by the combined coastal and terrestrial cells of the typology database). These comparisons provide several insights into the process of comparison and load estimation, and into the initial results for the critical class of drainage systems that dominate most of the world coastline.

Figures 3.21a and 3.21b illustrate the observation made previously that a second-order analysis is needed to refine the classification system used for initial explorations. In the case of population density, the two middle classes seem in need of boundary adjustment; there are few areas in the 1–10 people km^{-2} category, while the 10–100 category is large, uninformative and groups some regions together that seem intuitively disparate (e.g., NW Australia and W Alaska with parts of the Mediterranean and the Caribbean regions). The two middle classes are also problematic in the runoff classification. The 0.01–0.1 m yr^{-1} class represents little area, while the 0.1–1 m yr^{-1} class is excessively coarse, especially in view of the fact that it represents many of the highly developed coastlines as well as areas that would be expected to be more nearly pristine.

Figure 3.21c depicts the relative distribution of nutrient yields, derived from Figs. 3.21a and b and the regressions in Fig. 3.16. Yields can be expected to change with growing population even if we assume that the natural potential runoff will be more stable. Changes in load will reflect the area-weighted changes in yield. If most of the high-population coastal areas (Fig. 3.21a) are approaching saturation level in terms of human inputs and system responses, then the coastal systems may be relatively stable, if highly altered. On the other hand, most of these areas are experiencing continued growth and development. This is likely to be associated with still greater nutrient fluxes in the less developed countries and in areas of high to moderate runoff.

By linking expected changes in coastal zone fluxes to population projections we can identify some general geographic patterns of change now and, as we further assess the controls over both inputs and system response, we will be able to refine those expectations. We may also use the same approach to identifying the possible baseline or pristine areas, as discussed in Sect. 3.3.4.1. Figure 3.21 indicates that there are ample low-population, low-runoff areas to consider, but the situation is less clear for the more important moderate- to high-runoff, low-population density sites. There are relatively few low- and mid-latitude unaltered sites with runoff in the higher categories, and they tend to be close to areas that have a higher yield. This poses significant challenges to reconstructing baselines and natural mechanisms in these areas and reinforces the need for the refined analysis discussed above.

3.4 Conclusions

The LOICZ biogeochemical budgeting effort produced accomplishments in several areas:

- Improved understanding of the controls on biogeochemical fluxes and reactions in coastal systems, including an updated estimate of dissolved inorganic nutrient (N, P) loading to the ocean and its estimated geographic distributions and responses to human population and runoff.

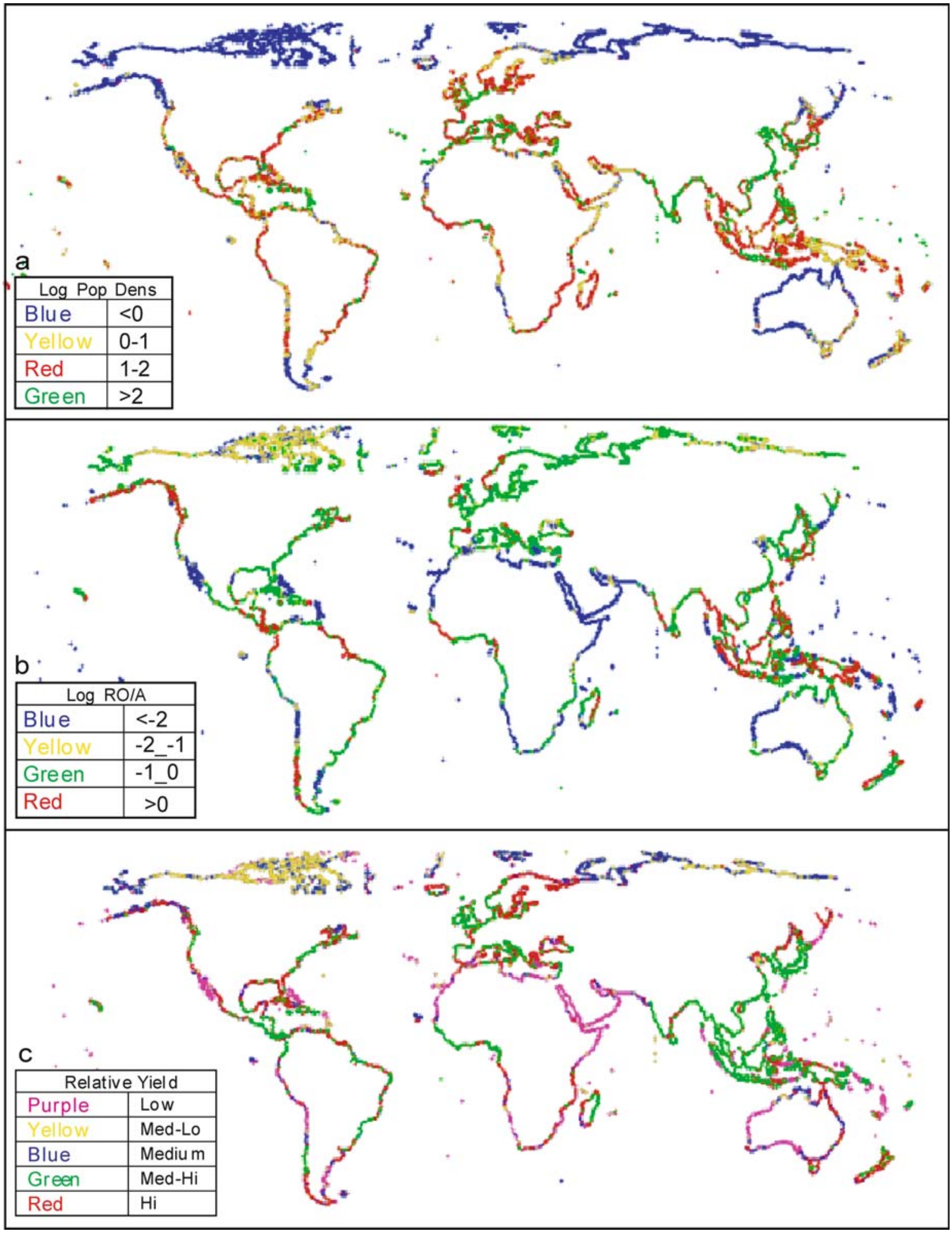


Fig. 3.21. Nutrient flux. Comparisons of present population density, runoff/area, and nutrient yields in small coastal basins (data used by Smith et al. 2003): **a** Four-class distribution of $\log_{10}$ population density (compare with PD axes in Figs. 3.17 and 3.18). **b** Four-class distribution of $\log_{10}$ runoff/area (compare with RO/A axes in Figs. 3.17 and 3.18). **c** Five clusters of DIP yield generated using the LOICZView tool. Cluster mean values are, from low to high: 0.1, 2.2, 28.2, 407 and 2138 moles $km^{-2}\,yr^{-1}$

- Conceptual understanding of the issues and potential approaches involved in cross-scale analyses and the effective upscaling of local observations, including identification of priority targets in terms of data needs, methods development, and geographic regions of particular interest.
- Infrastructure development, in the form of databases, tools and networks of scientists.

3.4.1 Biogeochemical Systems and Nutrient Loads

3.4.1.1 *Definition and Characterisation Issues*

Particulate materials tend to sediment near the sites of their delivery to the ocean, while reactive dissolved inorganic materials tend to react there. The strong negative log-log relationships seen between the absolute rates of the non-conservative fluxes (Figs. 3.13 and 3.14) and either system size or system exchange time argue that the most rapid rates of net material processing occur inshore, in small coastal systems linked to small coastal drainage basins. Since these small systems are typical of most of the length of the global coastline, integration of either the non-conservative fluxes of ΔDIP and ΔDIN or the derived fluxes of [$p - r$] and [nfix – denit] suggests that these rapid, inshore, small-system fluxes dominate global shelf fluxes, i.e., system size matters.

The flux dominance by small systems suggests that the importance of terrestrial input to the shelf is largely felt at a local (inner-shelf) scale, especially in bays and estuaries (see Text Box 3.14). These smaller-scale features rapidly process and respond to both natural and human inputs and are thus particularly sensitive to human modification.

At global to regional scales, changed inorganic nutrient loading to the coastal zone may have little impact on the shelves as a whole. If we look at the loading for the ocean as a whole, we observe that cycling between the deep ocean and surface ocean (for both N and P) and between the surface ocean and the atmosphere (for N) are far larger than the nutrient load from land (Michaels et al. 1996). Assuming that some small but significant fraction of this internal cycling exchanges with the open shelves (Thomas et al. 2004), changes in the terrestrial load are probably not generally significant at the scale of the shelves.

This contrast – between acute local effects on systems important to and exploited by humans and greatly attenuated far-field signals at a global scale – highlights the rationale for the basic LOICZ approach and explains many of the remaining challenges. Top-down, global-scale models can neither resolve nor represent the intensity and diversity of coastal zone functions.

3.4.1.2 *Updates of Nutrient Loads*

LOICZ results have led to an update of the estimates of dissolved inorganic nutrient (N, P) loading to the ocean, through development of a regression equation describing the logarithm of nutrient yield as a function of the logarithms of population density and runoff per unit area. These results have led to estimates of geographic distributions of that loading and load response to human population and runoff. The new estimates are substantially higher than those of Meybeck (1982) and somewhat elevated above the estimates shown in Figs. 1.1b and c. We have also used comparison with both Meybeck's pre-pollution estimates and our own low-load estimates to approximate pre-human inorganic nutrient loads to the ocean (Table 3.2).

Direct updates of either dissolved organic nutrient or particulate nutrient loads have not been developed, but the following general evaluations apply. Globally, inorganic nutrient loads seem likely to have changed the most; this is consistent with Meybeck. One might expect that greatly elevated erosion would have increased particulate nutrient delivery to the ocean. Based on analysis of the US (Smith et al. 2001), this seems not to be the case for particulate material in general in continental settings. Apparently most particulate erosion occurring at some distance from the coast yields products that have thus far remained mostly on land, especially where retained by dams and reservoirs. This is likely to be true of most large land masses with a relatively low perimeter/area ratio. However, in areas where most of the runoff and erosion originates from relatively small coastal basins, and especially in areas undergoing development, there is evidence for increasing net delivery to the ocean as a result of increased erosion.

These conclusions about the importance of system size and the nature of the nutrient yield relationships are important. However, both the results achieved and the lack of additional specific conclusions point to needs for further data and methods development. One need directly related to system and load characterisations concerns the use of ΔDIP as a proxy for organic carbon metabolism. This clearly works in some – but not all – systems. In particular, other reaction pathways, notably sorption and desorption of DIP with respect to sediment particles, interfere with the proxy. This is a particular problem for systems with high mineral turbidity. Yet the data simply do not yet exist to develop a large number of budgets or inventories based on reliable carbon data (see Text Box 3.5). Either an alternative approach must be found or methods must be developed to refine the DIP budgets.

The other identifiable needs are most clearly related to questions of scaling and relationships across temporal and spatial scales, natural domains and scientific disciplines.

Text Box 3.14. Regional variation of nutrient dynamics in the Baltic Sea

Dennis Swaney

The Baltic Sea is the most studied brackish water body in the world (see Wulff et al. 2001). It comprises three major sub-basins: (*i*) the Baltic Proper, which includes the Gulf of Finland and all of the region south of the Bothnian Sea to the Danish Straits, (*ii*) the Bothnian Sea, which separates much of Finland from Sweden, and (*iii*) the Bothnian Bay, which extends northward above the Bothnian Sea (Fig. TB3.14.1). Baltic Sea nutrient loading dynamics exhibit considerable variability within these regions. The northern drainage basin of the Baltic Sea extends well above the Arctic Circle, and the waters flowing from major drainage systems, such as the Luleälv (LE) in northern Sweden, are relatively nutrient-poor. Most of the loads to the Baltic Sea come from the south, into the Baltic Proper (as defined here), draining Eastern Europe and Russia (Fig. TB3.14.1).

Five major coastal ecosystems within the Baltic basin collectively dominate the freshwater and nutrient loads to the Baltic Sea. The Szczecin Lagoon (SL), the Gulf of Gdansk (GoG), the Curonian Lagoon (CL), the Gulf of Riga (GoR) and the Neva Estuary (NE) span the south-eastern coast of the Baltic Sea, and their rivers drain lands of Russia and "countries-in-transition" with rapidly changing environmental impacts. The drainage basins of the systems are large, ranging from 10^5 to 2.9×10^5 km^2, their spatial dimensions vary significantly and their average water residence times vary from two months (SL) to longer than two years (GoR). These systems have been subject to large anthropogenic nutrient loads, averaging 45 000 t yr^{-1} N (CL) to 140 000 t yr^{-1} N (GoG), and 2 000 t yr^{-1} P (GoR) to 7 000 t yr^{-1} P (GoG) from riverine sources alone. Despite these large loads, which account for about two-thirds of the riverine nutrient input to the Baltic, analysis of steady-state nutrient budgets suggests that significant differences exist, in terms of the proportion of the system loads which flow to the sea.

Wulff et al. (2001) and *http://data.ecology.su.se/mnode/Europe/BalticRegion/Baltic2001/baltic_seabud.htm* consider the Baltic Proper as a stratified system, as it has a marked permanent halocline, whereas the smaller, less saline basins of the Bothnian Sea and Bothnian Bay are well-mixed (Fig. TB3.14.2). Major DIP and DIN fluxes through these basins are noted in Figs. TB3.14.3 and TB3.14.4. Of particular interest is the near balance of autotrophy (upper layer) and heterotrophy (lower layer) in the Baltic Proper, and the excess of apparent denitrification over nitrogen fixation overall, despite the excess of nitrogen fixation over denitrification in the surface layer.

Also of interest is the strong latitudinal gradient in loading within the region (Table TB3.14.1). The northern regions, (e.g., the Luleälv basin) which drain into the Bothnian systems, have relatively low population densities and attendant impacts and are subject to the extremes of the Arctic environment. Nutrient loads are low, and the Luleälv estuary is heterotrophic and net nitrogen-fixing (Table TB3.14.2). This scarcity of nutrients is reflected in the metabolism of the Bothnian Bay, which is autotrophic and shows a net of nitrogen fixation over denitrification.

In the densely populated and agricultural regions of the southern Baltic, which feed the Baltic Proper, nutrient loads are high. Most of these coastal subsystems are autotrophic and denitrification exceeds nitrogen fixation, reflecting the abundance of available nutrients.

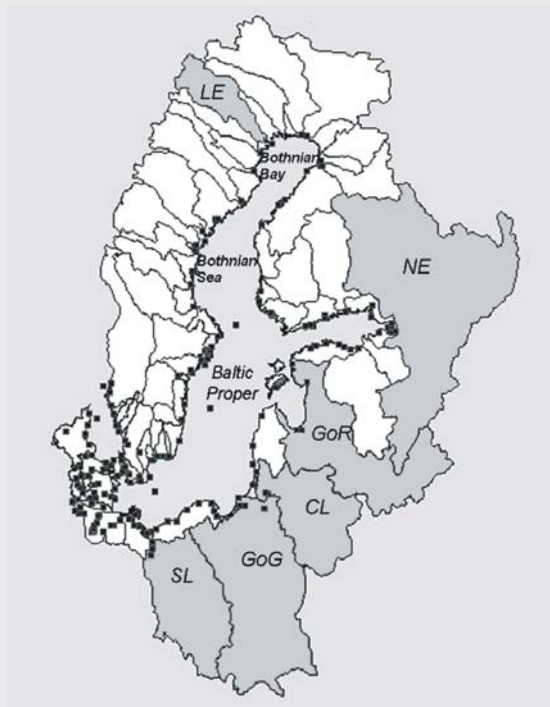


Fig. TB3.14.1. The Baltic Sea and its principal drainage basins. *Dots* indicate major point sources of nutrients

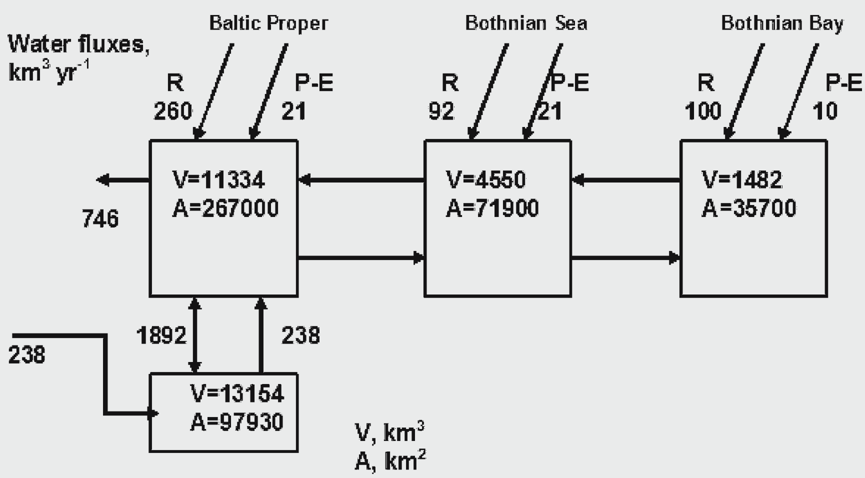


Fig. TB3.14.2. Water balance of the Baltic Sea (1975–90). Mean annual flows (km^3 yr^{-1}) and minimum and maximum flows for the period are shown as well as area (A, km^2) and volume (V, km^3) of each model box

◀

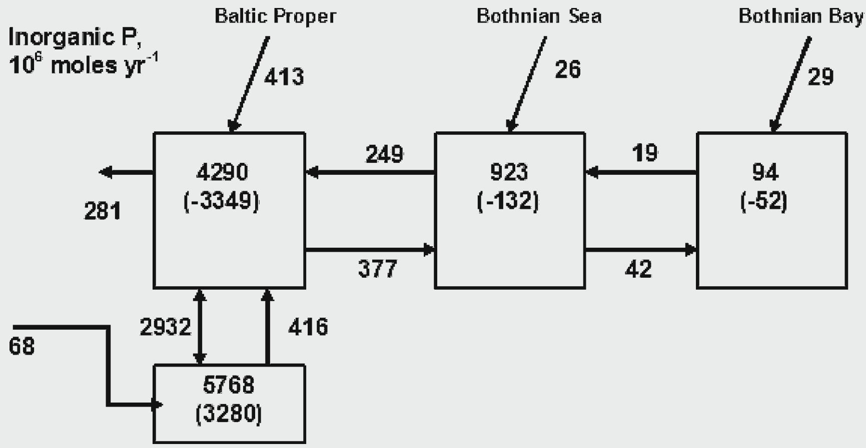


Fig. TB3.14.3. Inorganic phosphorus balance of the Baltic Sea (1975–90). Values inside boxes are the magnitudes of the P pool and the magnitudes of the estimated non-conservative flux of P (in parentheses)

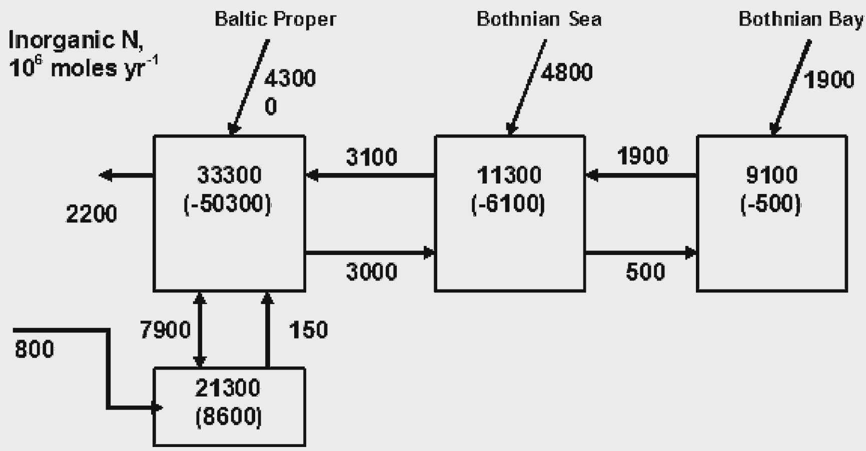


Fig. TB3.14.4. Inorganic nitrogen balance of the Baltic Sea (1975–90). Values inside boxes are the magnitudes of the N pool and the magnitudes of the estimated non-conservative flux of N (in parentheses)

Table TB3.14.1. Features and fluxes of some significant Baltic coastal systems

System	Surface area (km^2)	Drainage basin area (10^3 km^2)	Basin population density (ind. km^{-2})	Residence time (days)	*Vq* (km^3 yr^{-1})	DIP load (10^6 mole yr^{-1})	DIN load (10^6 mole yr^{-1})
Luleälven Estuary (LE)	50	–	–	12	9	1.2	65
Neva Estuary (NE)	1430	282	26	82	30	119	4300
Gulf of Riga (GoR)	16330	134	34	36	825	70	5800
Curonian Lagoon (CL)	1580	100	50	23	75	25	735
Gulf of Gdansk (GoG)	3250	194	123	38	15	183	6300
Sczeczin Lagoon (SL)	690	119	129	22	45	63	3300

3.4.2 Scale, Resolution and Generalisation

3.4.2.1 *Upscaling and Generalisation*

Successful extrapolation from the budget data to the global coastal zone requires three classes of globally available data in addition to the system-specific budget data and the techniques for linking them. Global datasets must permit characterisation of that portion of the land-atmosphere system delivering materials to a particular location (system or budget site) in the coastal zone, oceanic data for the specific system and oceanic data for the waters adjacent to and interacting with the system.

We have addressed the methodological issue of extrapolation from a relatively small number of budget

Text Box 3.14. *Continued*

Table TB3.14.2. Net ecosystem metabolism (NEM) of major Baltic Sea sub-basins and sub-systems

Basin/subsystem	ΔDIP (10^6 mole yr^{-1})	NEM (mmol C m^{-2} day^{-1})	ΔDIN (10^6 mole yr^{-1})	(nfix – denit) (mmol m^{-2} day^{-1})
Lulealven Estuary (LE)	1.6	–10	50	1.3
Neva Estuary (NE)	–51	10	–2 400	–3
Gulf of Riga (GoR)	–36	0.6	–4750	–0.7
Curonian Lagoon (CL)	7	–1.4	–99	–0.6
Gulf of Gdansk (GoG)	–211	19	–5 800	–2
Sczeczin Lagoon (SL)	–4	1.8	–2 270	–9
Baltic proper (combined layers)	69	–0.007	–41 700	–0.42
Bothnian Sea	–132	+0.53	–6 100	–0.15
Bothnian Bay	–52	+0.42	–500	0.025
Total Baltic Sea	–115	+0.14	–48 300	–0.32

sites to the global coastal zone primarily though use of powerful geo-statistical clustering tools initially developed for LOICZ applications (i.e., LOICZView [*http://www.palantir.swarthmore.edu/loicz*] and its successor application, DISCO [*http://narya.engin.swarthmore.edu/disco*]). The typology database developed for the project (Environmental Database link at *http://www.kgs.ku.edu/Hexacoral*) consists of data assembled at a grid scale of 0.5 degrees (areas > 2 000 km^2) for much of the globe; see Text Box 1.7, Chap. 1). This grid scale is dictated largely by the available global spatial datasets, most of which are at scales of 1 degree or coarser, and must be interpolated or sampled to smaller scales. At least for smoothly varying variables, this poses no particular analytical challenge, but variables with small-scale variation and/or discontinuities at the coastline are problematic.

On land, because most features are both spatially fixed and readily visible, global resolution to 1 km is available for many variables, making it possible to resample those data at the scale of the budget system watersheds, or catchment basins, a more natural or functional scale than the half-degree (0.5') grid. This higher-resolution subset of data on the catchment basins related to the budget sites has been used to develop process-based regression models of material fluxes, which were then extrapolated to the generally coarser and more artificial catchments defined by the half-degree grid spacing.

For the budgeted systems, the primary physical forcing data and chemical results have been obtained at scales appropriate to the site, along with system dimensions. However, the lack of an objective, spatially explicit "functional unit" for budget systems equivalent to catchment basins, together with the lack of spatial detail in available oceanic data, have so far precluded an equivalent analysis for either the budget systems themselves or the ocean region exchanging with any particular system.

In the ocean, the more rapid dynamics of water movement, the limited ability to describe visible sub-surface features and the importance of largely invisible chemical characteristics of the water place serious limits on the potential for developing high-resolution static representations. It is therefore impossible to use the coarsely defined marine data as a basis from which to classify or extrapolate the characteristics of small coastal features. Some alternative approach must be found.

3.4.2.2 *Heterogeneity and Functional Classification*

It is obvious that with decreasing system size comes increasing inter-system heterogeneity. The ocean is a large system in which most metabolism is accomplished by plankton with relatively rapid biotic turnover rates. Smaller sizes of systems, for example in the coastal zone, are locally dominated by plankton, benthic algae, seagrasses, coral reefs and mangroves. These systems differ greatly from one another; turnover times at the ecosystem level may be much slower than for planktonic systems and the response to perturbations is very different. Generalising globally therefore demands that each major type of system be adequately represented in the sampling and data analysis.

Heterogeneity can be expressed in terms of temporal as well as spatial characteristics, since larger systems tend to have longer water exchange times. Any budget or inventory approach to assessing the function of aquatic ecosystems has two broad classes of material transfer to deal with – physical transfer and biotic cycling. As a generality, the physical transfers have a wide dynamic range at small scales. For example, water flow can vary from near stagnant (< 1 mm sec^{-1}) to several meters per second (a range of orders of magnitude). As scales get larger, the *net* physical transfers are smaller; transfers occurring in opposite directions tend to average each other out. At the small scales, biotic transfers tend to have a much lower dynamic range. Although these processes also tend to balance at larger scales, the ability to see the small net effects of the biotic processes improves at larger scales because the biogeochemical budgets integrate rates over time. Large systems tend to have very long exchange times (Fig. 3.11) so they also have long integration times, which effectively modulate the results of small differences in the short-term rates. The most robust budgets involve relatively large systems with relatively long exchange times (e.g., the Baltic system, Shark Bay (Western Australia), Spencer Gulf (South Australia), the North Sea), but these systems are also characterised by low net biogeochemical rates. Small, active systems with short water exchange times represent an important part of the global coastal zone, but these systems tend not to yield robust estimates of fluxes because their short integration times result in noisy and variable integrated differences. Improved methodologies for obtaining widespread, reliable biogeochemical flux information are needed.

3.4.2.3 *Relevance to the Global Carbon Cycle*

Smith and Hollibaugh (1993) estimated that there is about 7×10^{12} mol yr^{-1} of net carbon oxidation in the coastal zone and 16×10^{12} mol yr^{-1} in the open ocean. The LOICZ analysis does nothing to alter this essential picture. In effect, this picture was based on establishing a globally robust budget for the entire ocean, which does not resolve the details of where the oxidation occurs. The local budgets give more understanding of the details but cannot be reliably added up to a global result. However, two aspects of this analysis of carbon flux are important to understanding coastal zone contributions. First, compared with estimated coastal and open ocean net primary production estimates of 500×10^{12} and $3\,000 \times 10^{12}$ mol yr^{-1}, respectively, the coastal ocean appears more heterotrophic ($p/r = 0.97$) than the open ocean ($p/r = 0.998$). Second, the apparent slight net heterotrophy of the global (coastal + open) ocean ($p/r = 0.994$; $[p - r] = -23 \times 10^{12}$ mol yr^{-1}) is an important part of understanding oceanic function and linkage to the slightly autotrophic land. Functionally, this net heterotrophy is quantitatively insignificant in terms of its influence on the ocean's role as a sink for anthropogenically generated CO_2. The overall oceanic CO_2 uptake is about 10 times greater than the CO_2 release due to net oceanic heterotrophy. On the 150-year time-scale over which humans have significantly perturbed the carbon cycle, the global oceanic CO_2 sink is dominated by inorganic processes – changing atmospheric partial pressure and the physical chemistry of seawater. On longer time-scales, the carbon sequestration roles of the ocean biological carbon pump (Karl et al. 2003) and the corresponding continental shelf pump (Chen et al. 2003) are influenced by both open ocean and coastal ocean biogeochemical processes.

3.4.3 Infrastructure and Methodology

LOICZ has made contributions to systematising and integrating coastal zone studies. These are alluded to in some of the conclusions listed above and in the recommendations that follow.

- Establishment, testing and dissemination of a standardised, widely applicable and easily used process for evaluating coastal system biogeochemical fluxes that permits intercomparison of the results of different studies and provides guidelines for measurements and surveys.
- Establishment of an internet-accessible environmental database that supports on-line manipulation and analysis as well as downloading of both budget site and global environmental data, and integrating those capabilities with other projects and consortia to ensure its sustainability and wider application.
- Development of on-line geospatial similarity analysis and visualisation tools (LOICZView, which has evolved to produce DISCO) that can be used with the LOICZ database or with independently supplied datasets.
- Pioneering the now widely-used approach of environmental typological analysis for functional classification and comparison of systems.
- Developing a world-wide network of scientists and environmental managers in both developing and developed countries who have common interests, problems, and the potential to benefit from the shared information and common methodologies of the larger community.

3.5 Recommendations

This section identifies priority areas for further research and assessment based on collective LOICZ experience, both specifically with regard to the biogeochemical budget effort and more generally in terms of its interactions with the other LOICZ activity areas. The first set of recommendations concerns conceptual and methodological developments desirable for extension of the fundamental LOICZ research and assessment activities in the area of coastal zone biogeochemical fluxes. Following this are more specific recommendations concerning LOICZ software tools and support.

3.5.1 Concepts and Methodology

The list below draws not only on the experience of the authors but also on the conceptual issues raised and substantive suggestions made by participants in LOICZ workshops, other collaborators and reviewers. We use three categories as a means of classifying scales of time and feasibility for the recommended activities:

1. Achievable with present data, technology and infrastructure, requiring only adequate funding and staffing.
2. Conceptually achievable with available or readily acquired data and tools, but requiring informational or institutional organisation and assembly and/or some development and testing as well as technical work.
3. "Blue sky" questions – needs that may or may not be feasible to meet and which would require significant new understanding, techniques or databases, but which are important and have the potential to transform our understanding.

Many of the recommended activities have aspects that belong in more than one category and are thus candidates for systematic, progressive exploration.

- *Category 1:*
  - Evaluate which additional (available or potentially available) data would be useful in improved budgets and system characterisations. Items for consideration could include more detailed information about the associated drainage basins, coastline, local coastal oceanography, dominant ecosystem and habitat type associated with each budgeted site. Test possible effects on sample systems.
  - Evaluate systematically the assumption of steady-state for various classes of coastal systems (e.g., incorporation of long-term trends, seasonal behaviour and episodic behaviour). For which regions of the world is it possible to go beyond steady-state? Where is it necessary?
  - Incorporate assessments of the uncertainty or error of budget terms into LOICZ methodology. The trade-off between the construction of a nutrient budget with high uncertainty in the values of its fluxes and its elimination for lack of information has been questioned. Specific consideration of this issue at the methodological stage would improve our ability to aggregate budgets for regional and global estimation and would suggest research needs in various regions.
- *Categories 1–2:*
  - Consider the effect of limitations on productivity other than P i.e., where does the assumption of a stoichiometric relationship between ΔDIP and NEM break down (e.g., limitation of light, nitrogen) and if it does, how can NEM be assessed?
  - Evaluate the utility and feasibility of constructing total N and total P budgets in conjunction with DIP and DIN budgets.
- *Category 2:*
  - Assess whether other "non-conservative fluxes" may be evaluated in the coastal zone (e.g., nutrient burial and sorption) and develop amended methodologies.
  - Extend nutrient budgets to budgets of other relevant materials (e.g., silica, dissolved oxygen, sediment) or at least evaluate and state where this might be feasible.
- *Categories 1–3:*
  - Consider and test the potential for fuller integration between the analysis of coastal systems and their drainage basins (e.g., breakdown of nutrient and sediment sources by source, consideration of terrestrial and aquatic processes which affect transport) either by modeling or detailed assessments.
- *Category 3:*
  - Test the application of multiple types of remote sensing to detailed coastal typologies and quantitative flux estimates. There have been major advances in remote determination of water depth, motion, colour and suspended sediment, potential for chlorophyll biomass and salinity, as well as precise measures of elevation, population and land cover. Unfortunately algorithms are not reliable for Coast II waters, which characterise much of the coastal zone. Future advances can be expected and integration of remotely sensed data may be able to fill many of the present gaps in both detail and resolution of the coastal databases.
  - Work toward a truly global interactive virtual network of coastal zone scientists, managers and relevant databases and tools, by building on the existing infrastructure and working to provide accessible, effective internet access to the entire international community.

Tools

Tools, websites and networks of both humans and data have been instrumental in the success of the project to date. The websites are an effective means of disseminating data and publications as well as supporting distance learning activities. The development of "mirror sites" should be considered. The use of tools should be strongly supported, to include:

- Expanded typology data access, including higher resolution data and more temporal components.
- On-line, interactive GIS visualisation and data input capabilities, both to enable users and to build toward the

necessary level of detail and resolution in developing the marine-system analogs of the watershed analyses.

- Active participation in the growing network of interoperable distributed database systems, such as the Open-DAP system and the Ocean Biogeographic Information System (OBIS).
- Simulation models of watershed-scale nutrient fluxes that can incorporate some of the recent findings from statistical analysis of LOICZ and other datasets, and which can be used to evaluate management and climate-change scenarios.
- Models of biogeochemical responses of the coastal zone to nutrient loads and other management-sensitive processes.
- Database systems, statistical tools, networks and coastal observing systems to take advantage of satellite imagery and other rapidly developing resources for measuring global and regional environmental processes and to link these global information resources with the local expertise needed to provide both ground truth and applications.

Some of these tools have been developed by LOICZ and can be further improved, reviewed, formalised and validated. Many others are still to be developed and utilised.

References

ADB (1997) Emerging Asia: changes and challenges. Asian Development Bank, Manila, Philippines

Atkinson MJ, Smith SV (1983) C:N:P ratios of benthic marine plants. Limnology and Oceanography 28:568–574

Baker S, Elderfield H (2002) Foraminiferal calcification response to glacial-interglacial changes in atmospheric CO_2. Science 297 (5582):833-836

Bartley JA, Buddemeier RW, Bennett DA (2001) Coastline complexity: a parameter for functional classification of coastal environments. Journal of Sea Research 46(2):87–97

Bennett EM, Carpenter SR, Caraco NF (2001) Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51:227–234

Berner RA (1982) Burial of organic carbon and pyrite sulfur in the modern ocean: its geochemical and environmental significance. American Journal of Science 282:451–473

Billen G, Lancelot C, Meybeck M (1991) N, P and Si retention along the aquatic continuum from land to the ocean. In: Mantoura RF, Martin JM, Wollast R (eds) Ocean margin processes in global change. WR Wiley & Sons, pp 19–44

Botero L (1990) Massive mangrove mortality on the Caribbean coast of Colombia. Vida Silvestre Neotropical 2:77–78

Boyd PW, Doney SC (2003) The impact of climate change and feedback processes on the ocean carbon cycle. In: Fasham MJR (ed) Ocean biogeochemistry. Springer Verlag, Berlin, pp 157–193

Buddemeier, RW, Smith SV, Swaney DP, Crossland CJ (2002) The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles. LOICZ Reports & Studies, LOICZ, Texel, The Netherlands, No. 24

Canfield DE (1989) Sulfate reduction and oxic respiration in marine sediments: implications for organic carbon preservation in euxinic environments. Deep-Sea Research 36:121–138

Caraco NF, Cole JJ (1999) Human impacts on nitrate export: an analysis using major world rivers. Ambio 28:167–170

Cardona P, Botero L (1998) Soil characteristics and vegetation structure in a heavily deteriorated mangrove forest in the Caribbean coast of Colombia. Biotropica 30:24–34

Chen C-TA, Liu KK, Macdonald R (2003) Continental margin exchanges. In: Fasham MJR (ed) Ocean Biogeochemistry. Springer, Berlin, pp 53–97

Coale KH, Johnson KS, Fitzwater SE, Gordon RM, Tanner S, Chavez FP, Ferioli L, Sakamoto C, Rogers P, Millero F, Steinberg P, Nightingale P, Cooper D, Cachlan WP, Landry MR, Constantinou J, Rollwagen G, Trasvina A, Kudela R (1996) A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. Nature 383:495–501

Conley DJ, Malone TC (1992) Annual cycle of dissolved silicate in Chesapeake Bay: implications for the production and fate of phytoplankton biomass. Marine Ecology Progress Series 81:121–128

Conley DJ, Schelske CL, Stoermer EF (1993) Modification of the biogeochemical cycle of silica with eutrophication. Marine Ecology Progress Series 101:179–192

Cooper SR, Brush GS (1991) Long-term history of Chesapeake Bay anoxia. Science 254:992–996

Couto ECG, Zyngier NAC, Gomes VR, Knoppers BA, Landim de Souza MF (2002) Marica-Guarapina coastal lagoons, Rio de Janeiro State. In: Dupra V, Smith SV, Marshall Crossland JI, Crossland CJ (eds) Estuarine systems of the South American region: carbon, nitrogen and phosphorus fluxes. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No.15, pp 19–21

da Silva A, Young AC, Levitus S (1994) Atlas of surface marine data 1994, vol 1: Algorithms and procedures. NOAA Atlas NESDIS 6, US Department of Commerce, Washington, DC (also: *http://ingrid.ldgo.columbia.edu/SOURCES/.DASILVA/.SMD94/.halfbyhalf/*)

Delgadillo F, Segovia Zavala JA (1997) Bahia San Luis Gonzaga, Baja California. In: Smith SV, Ibarra-Obando S, Boudreau PR, Camacho-Ibar VF (eds) Comparison of carbon, nitrogen and phosphorus fluxes in Mexican coastal lagoons. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No. 10 pp 16–20.

Dortch Q, Rabalais NN, Turner RE, Qureshi NA (2001) Impacts of changing Si/N ratios and phytoplankton species composition. In: Rabalais NN, Turner RE (eds) Coastal hypoxia: consequences for living resources and ecosystems. Coastal and estuarine studies. American Geophysical Union, pp 37–48

Downing JA, McClain M, Twilley R, Melack JM, Elser J, Rabalais NN, Lewis WM, Turner RE, Corredor J, Soto D, Yanez-Arancibia A, Howarth RW (1999) The impact of accelerating land-use change on the N-cycle of tropical aquatic ecosystems. Geochemistry 46:109-148

Dugdale RC, Wilkerson FP (1998) Silicate regulation of new production in the eastern equatorial Pacific. Nature 391:270:273

Dunteman GH (1989) Principal components analysis. Sage Publications, Newbury Park, CA

Dupra VC (2003) Nutrient fluxes in various coastal ecosystems of the South China Sea perturbed by human activities. Masters Thesis, Marine Science Institute, University of the Philippines

Dupra V, Smith SV, Marshall Crossland JI, Crossland CJ (2000a) Estuarine systems of the South China Sea region: carbon, nitrogen and phosphorus fluxes. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No. 14

Dupra V, Smith SV, Marshall Crossland JI, Crossland CJ (2000b) Estuarine systems of the East Asia region: carbon, nitrogen and phosphorus fluxes. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No. 16

Frankignoulle M, Abril G, Borges A, Bourge I, Canon C, DeLille B, Libert E, Theate J-M (1998) Carbon dioxide emission from European estuaries. Science 282:434–436

Froelich PN (1988) Kinetic control of dissolved phosphate in natural rivers and estuaries: a primer on the phosphate buffer mechanism. Limnology and Oceanography 33:649–668

Furnas M(2003) Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science, Townsville, Australia

Galloway JN, Cowling EB (2002) Reactive nitrogen and the world: 200 years of change. Ambio 31:64–71

Gattuso J-P, Frankignoulle M, Smith SV (1999) Measurement of community metabolism and significance in the coral reef source-sink debate. Proceedings of the National Academy of Science 96:13017–13022

GEMS (1996) Annotated digital atlas of global water quality. GEMS Water Collaborating Center, Ontario, Canada. Diskette and at *http://www.cciw.ca/gems/intro.html*

Gordon DC Jr, Boudreau PR, Mann KH, Ong J-E, Silvert WL, Smith SV, Wattayakorn G, Wulff F, Yanagi T (1996) LOICZ Biogeochemical Modelling Guidelines. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No.5

Guinotte JM, Buddemeier RW, Kleypas JA (2003) Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22 (4):552–558

Hall J, Smith SV, Boudreau PR (eds) (1996) Report on the international workshop on continental shelf fluxes of carbon, nitrogen and phosphorus. LOICZ Reports and Studies No. 9/JGOFS Report No. 22, LOICZ, Texel, The Netherlands

Hedges JI, Keil RG (1995) Sedimentary organic matter preservation: an assessment and speculative synthesis. Marine Chemistry 49:81–115

Holligan PM, Reiners WA (1992) Predicting the responses of the coastal zone to global change. Advances in Ecological Research 22:211–255

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001) Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge UK, New York USA (*http://www.ipcc.ch/*)

Howarth, RW, Billen G, Swaney D, Townsend A, Jaworski N, Lajtha K, Downing JA, Elmgren R, Caraco N, Jordan T, Berendse F, Freney J, Kudeyarov V, Murdoch P, Zhao-Liang Z (1996) Regional nitrogen budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. Biogeochemistry 35:75–139

Humborg C, Conley DJ, Rahm L, Wulff F, Cociasu A, Ittekkot V (2000) Silicon retention in river basins: far-reaching effects on biogeochemistry and aquatic food webs in coastal marine environments. Ambio 29(1):45–50

Ittekkot V, Humborg C, Schafer P (2000) Hydrological alterations and marine biogeochemistry: a silicate issue? BioScience 50(9): 776–782

Jacobson MC, Charlson RJ, Rohde H, Orians GH (2000) Earth system science. International Geophysics Series, Academic Press, Amsterdam, vol 72

Jaffe DA (2000) The nitrogen cycle. Chapter 12 in: Jacobson MC, Charlson RJ, Rohde H, Orians GH (2000) Earth system science. International Geophysics Series, Academic Press. Amsterdam, vol 72, pp 322–342

Jahnke RA (2000) The phosphorus cycle. Chapter 14. In: Jacobson MC, Charlson RJ, Rohde H, Orians GH (2000) Earth System Science. International Geophysics Series, Academic Press. Amsterdam, vol 72, pp 360–376

Jickells TD (1998) Nutrient biogeochemistry of the coastal zone. Science 281:217–222

Justic D, Rabalais NN, Turner RE, Dortch Q (1995) Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. Estuarine, Coastal and Shelf Science 40:339–356

Karl DM, Bates NR, Emerson S, Harrison PJ, Jeandel C, Llinás O, Liu K-K, Marty J-C, Michaels AF, Miquel JC, Neuer S, Nojiri Y, Wong CS (2003) Temporal studies of biogeochemical processes determined from ocean time-series observations during the JGOFS era. In: Fasham MJR (ed) Ocean Biogeochemistry. Springer, Berlin, pp 237–267

Keeling CD, Whorf TP, Wahlen M, van der Plicht J (1995) Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. Nature 375:666–670

Kleypas JA, Buddemeier RW, Archer D, Gattuso J-P, Langdon C, Opdyke BN (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science 284:118–120

Kleypas JA, Buddemeier RW, Gattuso J-P (2001) The future of coral reefs in an age of global change. International Journal of Earth Sciences 90:426–437

Langdon C, Takahashi T, Sweeney C, Chipman D, Goddard J, Marubini F, Aceves H, Barnett H, Atkinson M (2000) Effect of calcium carbonate saturation state on the rate of calcification of an experimental coral reef. Global Biogeochemical Cycles 14:639–654

Laws E (1997) Mathematical methods for oceanographers. Wiley, New York, USA

Marubini F, Ferrier-Pages C, Cuif J-P (2003) Suppression of growth in scleractinian corals by decreasing ambient carbonate ion concentration: a cross-family comparison. Proceedings of the Royal Society B 270(1511):179–184

Maxwell BA, Buddemeier RW (2001) Coastal typology development with heterogeneous data sets. Regional Environmental Change 3:77–87

Meybeck M (1982) Carbon, nitrogen and phosphorus transport by world rivers. American Journal of Science 282:401–450

Meybeck M (1998) The IGBP water group: a response to a growing global concern. Global Change Newsletter 36:8–12

Meybeck M, Ragu A (1997) River discharges to the oceans: an assessment of suspended solids, major ions and nutrients. GEMS/EAP Report

Meybeck M, Chapman D, Helmer R (1989) Global water quality. WHO/UNEP, Blackwell Inc, Oxford

Michaels AF, Olson D, Sarmiento J, Ammerman J, Fanning K, Jahnke R, Knap AH, Lipschultz F, Prospero J (1996) Inputs, losses and transformations of nitrogen and phosphorus in the pelagic North Atlantic Ocean. Biogeochemistry 35:181–226

Milliman JD, Droxler AW (1996) Neritic and pelagic carbonate sedimentation in the marine environment: ignorance is not bliss. Geologische Rundschau 85:496–504

Milliman JD, Syvitski JPM (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology 100:525–544

Nedwell DB, Kickells TD, Trimmer M, Sanders R (1999) Nutrients in estuaries. Advances in Ecological Research 29:43–92

Nixon SW (1995) Coastal marine eutrophication: a definition, social causes and future concerns. Ophelia 41:199–219

Nixon SW, Ammerman JW, Atkinson LP, Berounsky VM, Billen G, Boicourt WC, Boynton WR, Church TM, Ditoro DM, Elmgren R, Garber JH, Giblin AE, Jahnke RA, Owen NJP, Pilson MEQ, Seitzinger SP (1996) The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry 35:141–180

Officer CB, Ryther JR (1980) The possible importance of silicon in marine eutrophication. Marine Ecology Progress Series 3:83–91

Pernetta, JC, Milliman JD (1995) Land-Ocean Interactions in the Coastal Zone – Implementation Plan. IGBP Report 33

Prentice IC, Farquhar GD, Fasham MJR, Goulden ML, Heiman M, Jaramello VJ, Kheshgi HS, Le Quere C, Scholes RJ, Wallace DWR (2001) The carbon cycle and atmospheric carbon dioxide. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge U.K. and New York, USA, pp 183–239

Rabalais NN, Turner RE, Scavia D (2002) Beyond science and into policy: Gulf of Mexico hypoxia and the Mississippi River. BioScience 52:129–142

Redfield AC (1958) The biological control of chemical actors in the environment. American Scientist 46:205–222

Redfield AC, Ketchum BH, Richards FA (1963) The influence of organisms on the composition of sea-water. In: Hill MN (ed) The Sea, vol 2, pp 26–77

Reeburgh WS (1983) Rates of biogeochemical processes in anoxic sediments. Annual Review of Earth & Planetary Science 11:269–298

Ricker WE (1973) Linear regression in fisheries research. Journal of the Fisheries Research Board of Canada 30(3):409–434

Riebesell U, Zondervan I, Rost B, Tortell PD, Zeebe RE, Morel FM (2000) Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature 407:364–367

Rivera-Monroy VH, Jonsson BF, Twilley RR, Casas-Monroy O, Castaneda E, Montiel R, Mancera E, Troncoso W, Daza-Monroy F (2002) Cienaga Grande de Santa Maria: a tropical coastal lagoon in a deltaic geomorphic setting. In: Camacho-Ibar V, Wulff F, Dupra V, Smith SV, Marshall Crossland JI, Crossland CJ (2002) Estuarine systems of the Latin American region (Regional Workshop V) and estuarine systems of the Arctic region: carbon, nitrogen and phosphorus fluxes. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No. 23, pp 22–27

San Diego-McGlone ML, Smith SV, Nicolas VF (2000) Stoichiometric interpretations of C:N:P ratios in organic waste materials. Marine Pollution Bulletin 40:325–330

Sandhei PT (2003) Effects of land use on the concentration of dissolved inorganic nitrogen and phosphorus in global stream systems. M.S. Thesis, Geography, University of Kansas, Lawrence, Kansas

Sarmiento JL, Sundquist ET (1992) Revised budget for the oceanic uptake of anthropogenic carbon dioxide. Nature 356:589–593

Scavia D, Field JC, Boesch DF, Buddemeier RW, Burkett V, Cayan DR, Fogarty M, Harwell MA, Howarth RW, Mason C, Reed DJ, Royer TC, Sallenger AH, Titus JG (2002) Climate change impacts on US coastal and marine ecosystems. Estuaries 25:149–164

Schimel DS (1995) Terrestrial ecosystems and the carbon cycle. Global Change Biology 1:77–91

Schindler DW (1999) The mysterious missing sink. Nature 398: 106–109

Schlesinger WH (1997) Biogeochemistry, 2nd edn. Academic Press, San Diego

Scialabba N (1998) Integrated coastal zone management and agriculture, forestry and fisheries. FAO Guidelines. Environment and Natural Resources Service, FAO, Rome

Seitzinger SP (1988) Denitrification in freshwater and coastal marine ecosystems: ecological and geochemical significance. Limnology and Oceanography 33:702–724

Seitzinger SP, Kroeze C, Bouwman AF, Caraco N, Dentener F, Styles RV (2002) Global paterns of dissolved inorganic and particulate nitrogen input to caostal systems: recent contributions and future projections. Estuaries 25:640-655

Smayda TJ (1990) Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic. In: Granéli E, Sundström B, Edler R, Anderson DM (eds) Toxic marine phytoplankton. Elsevier, New York, pp 29–40

Smith SV (1985) Physical, chemical and biological characteristics of CO_2 gas flux across the air-water interface. Plant, Cell and Environment 8:387–398

Smith SV, Hollibaugh JT (1993) Coastal metabolism and the oceanic organic carbon balance. Reviews of Geophysics 31:75–89

Smith SV, Mackenzie FT (1987) The ocean as a net heterotrophic system: implications from the carbon biogeochemical cycle. Global Biogeochemical Cycles 1:187–198

Smith SV, Renwick WH, Buddemeier RW, Crossland CJ (2001) Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15:697–707

Smith SV, Swaney DP, Talaue-McManus L, Bartley JD, Sandhei PT, McLaughlin CJ, Dupra VC, Crossland CJ, Buddemeier RW, Maxwell BA, Wulff F (2003) Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. BioScience 53:235–245

Sokal RL, Rohlf FJ (1995) Biometry, 3rd edn. WH Freeman, New York,

Stallard RF (1998) Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12:231–257

Stewart JS (2000) Tidal energetics: studies with a barotropic model. PhD thesis, University of Colorado, Boulder, CO.

Sverdrup HU, Johnson MW, Fleming RH (1942) The oceans. Prentice-Hall, New York

Takahashi T, Broecker WS, Langer S (1985) Redfield ratio based on chemical data from isopycnal surfaces. Journal of Geophysical Research 90:6907–6924

Talaue-McManus L (2000) Transboundary diagnostic analysis for the South China Sea. EAS/RCU Technical Report Series No. 14. UNEP, Bangkok, Thailand

Talaue-McManus L, Kremer HH, Marshall-Crossland JI (2001) SARCS/WOTRO/LOICZ: biogeochemical and human dimensions of coastal functioning and change in Southeast Asia. Final report of the SARCS/WOTRO/LOICZ project 1996–1999. LOICZ Reports and Studies, LOICZ, Texel, The Netherlands, No.17

Thom BG (1982) Mangrove ecology: a geomorphological perspective. In: Snedekar SC, Snedakar JG (eds) The mangrove ecosystem: research methods. UNESCO, Paris, pp 3–7

Thomas H, Bozec Y, Elkalay K, de Baar HJW (2004)Enhanced open ocean storage of CO_2 from shelf sea pumping. Science 304: 1005–1008

Turner RE, Rabalais NN (1991) Changes in Mississippi River water quality this century and implications for coastal foodwebs. Bioscience 41:140-147

Turner RE, Quveshi N, Rabalais NN, Dortch Q, Justic D, Shaw RF, Cope J (1998) Fluctuating silicate:nitrate ratios and coastal plankton food webs. Proceedings National Academy of Science, USA 95:13048-13051Twilley RR, Rivera-Monroy VH, Chen R, Botero L (1999) Adapting an ecological mangrove model to simulate trajectories in restoration ecology. Marine Pollution Bulletin 37:404–419

USGS (2001) Hydro1K elevation derivative database. United States Geological Survey. *http://edcdaac.usgs.gov/gtopo30/hydro/*

van Drecht G, Bouwman AF, Koop JM, Meinardi C, BeusenA (2001) Global pollution of surface water from point and non-point sources of nitrogen. The Scientific World, vol 1, pp 632–641

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alterations of the global nitrogen cycle: sources and consequences. Ecological Applications 7:737–750

Ware JR, Smith SV, Reaka-Kudla ML (1992) Coral reefs: sources or sinks of atmospheric Co_2? Coral Reefs 11:127–130

Watson A, Whitfield M (1985) Composition of particles in the global ocean. Deep-Sea Research 32:1023–1039

Webster IT, Parslow JS, Smith SV (2000) Implications of spatial and temporal variation for biogeochemical budgets of estuaries. Estuaries 23: 341–350

WRI (2000) World resources 2000–2001. People and ecosystems. The fraying web of life. World Resources Institute, Washington DC, USA

Wulff F, Rahm L, Larsson P (2001) A systems analysis of the Baltic Sea. Springer-Verlag, Berlin

Chapter 4

The Catchment to Coast Continuum

Wim Salomons, Hartwig H. Kremer and R. Kerry Turner
Contributors: *Elena N. Andreeva, Russell S. Arthurton, Horst Behrendt, Peter Burbridge, Chen-Tung Arthur Chen, Christopher J. Crossland, Jürgen Gandrass, Vjacheslav V. Gordeev, Nick Harvey, G. H. Hong, Bjorn Kjerfve, L. D. de Lacerda, Janet I. Marshall Crossland, Nicole Morcom, Eric Odada, Jozef Pacyna, Nancy N. Rabalais, Dennis Swaney, William J. Wiebe*

4.1 Introduction

The policy and management challenge for coastal zones is to ensure the sustainable availability of coastal resources under intense pressure from environmental change. However, much of the environmental change pressures originate not from within the coastal zone but from the catchments, or river basins, that feed freshwater and materials into the coastal zone. Riverine inputs, along with oceanic forces, influence the geomorphology and availability of natural resources of the coastal zone. The linkages between catchment–coastal processes and systems, the influence of climatic change and the impacts on and feedback effects from socio-economic activity are still poorly understood.

One approach to better understanding of the catchment–coast linkage is to use retrospective information from the system in order to make predictions about its future behaviour. This requires an in-depth analysis of changes in processes and impacts that are the result of change in the biophysical system or its inherent variability and of those due to human impacts on the biophysical system (e.g., coastal engineering, conversion of wetlands, fishing) that have led to a significant loss of coastal ecosystems and resources. Less well-known are the indirect changes originating from the catchment basin that cause changes in flow of freshwater, sediments (Syvitski 2003, Syvitski et al. 2005), nutrients (Smith et al. 2003) and contaminants. The impacts of indirect changes are influenced by the source of the change, the time-scale over which it operates and the interaction of natural and socio-economic variables on the system (Fig. 4.1).

4.1.1 The LOICZ-Basins Approach

During the LOICZ-Basins study, not all the components of Fig. 4.1 could be considered within the available resources and time-frame. Attention was given to assessments across a time-frame of 20 to 30 years. The impact of differences in biophysical and socio-economic conditions on fluxes and their subsequent impact on the coastal zone were considered. In some cases, attention was paid to climate change. However, the challenge of identifying differences in culture and values was not met, (time-frames of hundreds of years) nor their effect on public policy and perceptions of coastal zone impacts.

Within LOICZ, a standardised framework of analysis was developed to assess the impact of land-based sources, in particular catchment basins, on coastal systems (see Chap. 1 and Text Box 4.1). About 100 catchment–coastal sea systems have been analysed through workshops and desk studies. In addition, individual assessments were scaled up to continental regions. The activities of LOICZ-Basins have also resulted in more detailed studies of catchments in Africa (AfriCat) and in Europe (EuroCat) (Fig. 4.2).

In the LOICZ-Basins assessments, the coastal sea and its associated catchment(s) are treated as one system and evaluated by consideration of the elements of the Driver–Pressure–State–Impact–Response (DPSIR) framework (Text Box 4.1; Fig. 4.3). The coastal response to land-based activities is determined against socio-economic activities so that results from natural and socio-economic sciences have to be combined (Turner et al. 1998, Salomons et al. 1999). For instance, impacts of socio-economic activities are modified by the biophysical settings of the catchment-coast-sea system. A similar level of socio-eco-

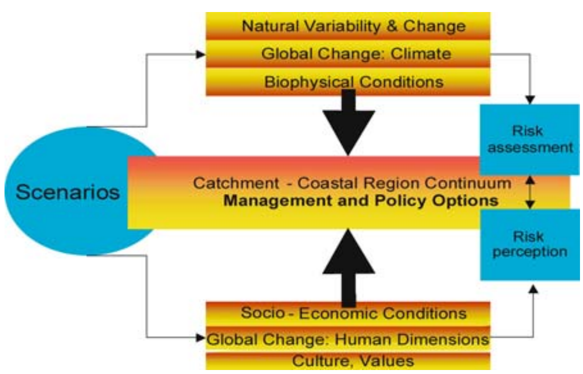


Fig. 4.1. LOICZ-Basins. Natural and socio-economic inter-linkage in the catchment–coast continuum

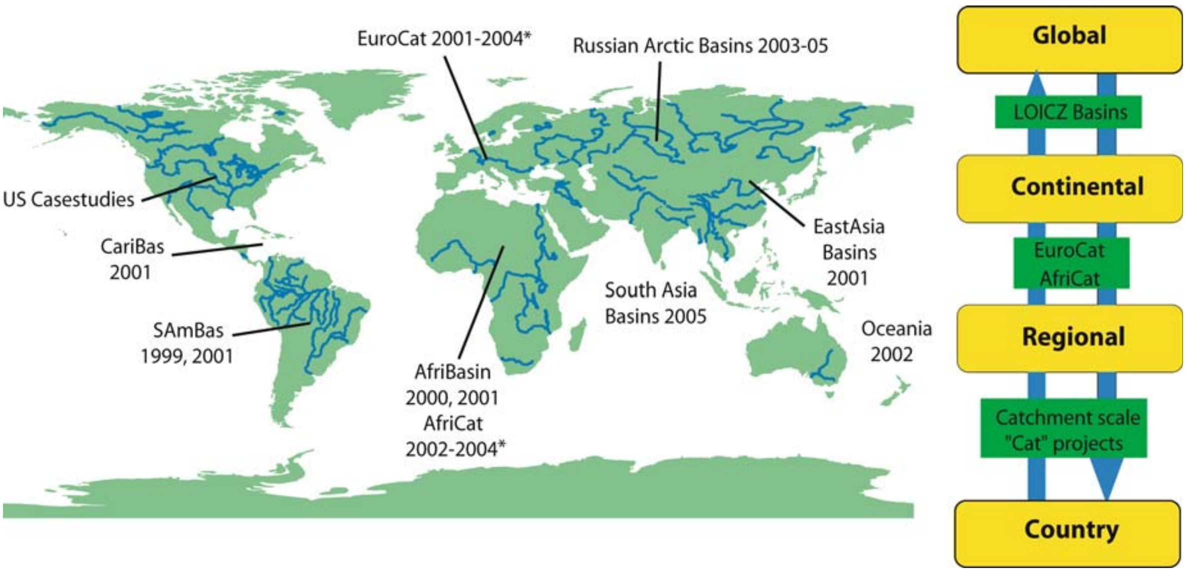
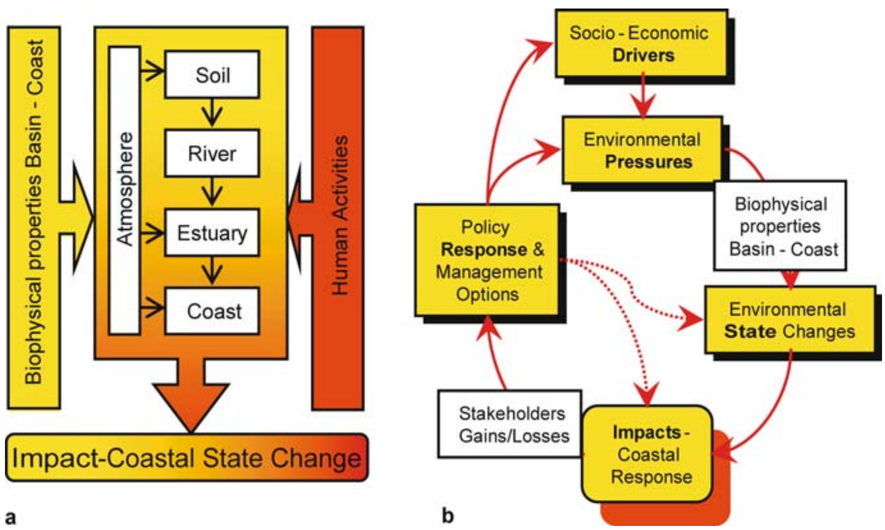


Fig. 4.2. LOICZ-Basins Catchments and coastal regions evaluated (* resulting research projects)

Fig. 4.3. LOICZ-Basins. **a** The catchment-coast continuum as one system; **b** the DPSIR framework



nomic activity in a small mountainous river system will have a different impact on the receiving coastal zone than a large lowland river system.

Large catchments would at first seem to be obvious examples to be addressed within a global LOICZ synthesising effort (e.g., Amazon, Nile, Yangtze, Orinoco). However, from the perspective of coastal change, the major influence from land-based flows is more often generated by small to medium catchments with high levels of socio-economic activity. In small to medium catchments, changes in land cover and use need much shorter timeframes to translate into coastal change, and for any given magnitude of change usually exhibit more visible impacts than changes within large catchments where the "buffer capacity" against land-based change is higher, simply as a function of basin size. Thus, small and medium catchments are a priority for the global LOICZ-Basins assessment. They dominate the global coastal zone (in Africa, for example, they characterise extensive parts of monsoon-driven runoff to the Indian Ocean).

The LOICZ-Basins assessment follows a hierarchy of scales which generate a composite regional picture. The scales range from:

- local catchments, to
- national or sub-regional or provincial levels, to
- full regional i.e., sub-continental or even continental.

The steps taken in an assessment are:

1. production of a list of coastal change issues and related drivers in the catchment.

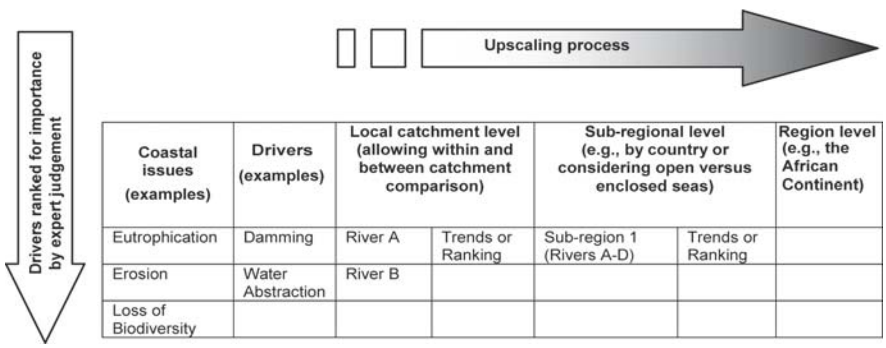
Text Box 4.1. The Driver-Pressure-State-Impact-Response Framework

Wim Salomons, Hartwig H. Kremer, R. Kerry Turner

The Driver-Pressure-State-Impact-Response (DPSIR) scheme (Turner et al. 1998, Turner and Bower 1999) provides a standardised framework for site assessment and evaluation and adopts a systems approach. The elements of the framework are:

- *Drivers:* resulting from societal demands, these are the activities with consequences for the coastal zone and include: urbanisation, aquaculture, fisheries, oil production and pro-cessing, mining, agriculture and forestry, industrial development, ports and harbour development and other land-use changes.
- *Pressures:* processes affecting key ecosystem and social system functioning (i.e., natural and anthropogenic forcing affecting and changing the state of the coastal environment), including: damming and other constructions, river diversion, irrigation and water abstraction, industrial effluents (industrialisation), agricultural runoff, domestic wastes (urbanisation), navigation and dredging, sea-level rise induced by land-based activities or groundwater abstraction affecting the coastal zone (e.g., decrease of riverine sediment load leading to instability of coastal geomorphology) and other forcing functions, such as climate change.
- *State and state change:* the indicator functions and how they are affected, for example: water, nutrient and sediment transport (including contaminants where appropriate) observed in the coastal zone as key indicators for trans-boundary pressures within the water pathway. Indicators are designed to give an overview of the environmental status and its development over time and ultimately enable derivation of assimilative capacity limits, geomorphologic settings, erosion, sequestration of sediments, siltation and sedimentation, economic fluxes relating to changes in resource stocks and flows and changes in economic activity in monetary and other terms.
- *Impact:* effects on system characteristics and provision of goods and services, for example: habitat alteration, changes in biodiversity, social and economic functions, resource and services availability, use and sustainability and depreciation of the natural capital stock.
- *Response:* action taken at a political and/or management level that can include scientific responses (research efforts, monitoring programs) as well as policy and/or management response to either protect against changes, such as increased nutrient or contaminant input, secondary sea-level rise, or to ameliorate and/or rehabilitate adverse effects and ensure or re-establish the chance for sustainable use of the system's resources.

Fig. 4.4.
LOICZ-Basins. Schema of assessment tables



2. characterisation and ranking of the various issues of change, based on either qualitative (i.e., expert judgement) or quantitative (data) information. This step includes identification of critical load and threshold information for system functioning where available (e.g., Kjerfve et al. 2002, Lacerda et al. 2002, Gordeev et al. 2005).

Thus, LOICZ-Basins provides a typology of the current state and expected trends of coastal change under land-based human forcing and natural influences. The assessment follows a set of key questions that cover the various aspects and scales of the DPSIR analysis and utilises a sequence of assessment tables (Fig. 4.4). An example of the questions and upscaling procedure is presented in Fig. 4.5, using the results of the assessment of the South American sub-continent. The ranking of drivers, pressures, impacts and trends (synthesis tables in Fig. 4.5) is based on expert judgement but backed up by data from relevant literature. Detailed results (down to individual catchment scale) and the literature references can be found in the individual reports (see *www.loicz.org* and Appendix A.1).

In this chapter we summarise and focus on the regional and sub-regional scales. The regional-continental results are discussed in the main text; individual assessments of catchment basins can be found in the LOICZ-Basins reports (see Appendix A.1). The upscaling to sub-regions and sub-continental or continental scale is illustrated in partly coloured tables where green, yellow and red indicate the sequence of increased ranking of importance or decreasing, stable or increasing trend expectations respectively. The results from the relatively smaller (in terms of land area and population) and partly island dominated assessed areas of the Caribbean and Oceania regions are presented below in Text Boxes 4.2 and 4.3. For Europe the initial regional assessments were extended using a scenario-building approach to provide a set of considered options and outcomes of relevance to management interests.

Key issues addressed in the Basins approach

- gaps in current understanding of river catchment-coast interaction, future hotspots calling for priority scientific attention

Full regional/continental Synthesis

Ranking drivers and issues	Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectation	Sub-regions particularly affected
1	Urbanisation	Eutrophication	Major	⇑	1,2,3,4,6,7
2	Damming/ diversion	Erosion/sedimentation	Major	⇑	2,4,5,7,8
3	Deforestation	Erosion/sedimentation	Medium	⇑	1,2,6,7,8
4	Industrialisation	Pollution	Medium	⇑	1,2,6,7
5	Agriculture	Eutrophication/pollution	Medium	⇑	2,4,7,8
6	Aquaculture	Eutrophication	Minor	⇑	1,2,5
7	Navigation	Erosion/sedimentation	Minor	⇒	2,4,7
8	Fisheries	Loss of biodiversity	Minor	⇒	5,6,7
9	Tourism	Erosion/eutrophication	Minor	⇑	5,6
10	Mining	Erosion/pollution	Minor	⇓	5,8

- level of scientific and/or policy and management response

Sub-regional division based on climatic, geographic, population or land-use characteristics

Sub-regional Synthesis

Sub-region 6 · Central Brazilian Atlantic Coast, Guanabara & Sepetiba Bay			
Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Erosion/sedimentation	Major	⇑
Industrialisation	Pollution	Medium	⇑
Deforestation	Erosion/sedimentation	Medium	⇑
Tourism	Erosion/eutrophication	Minor	⇑
Fisheries	Loss of biodiversity	Minor	⇒

- future trends and scenarios of river catchment-based coastal change and impact

Expert assessment and qualitative ranking from catchment scale to continental scale

- spatial scales where certain driver/pressure settings dominate coastal change (i.e. catchment, sub-regional, country or continental)

- major driver/pressure settings on river catchment scale

- major land-based coastal impacts (issues) and critical thresholds for system functioning

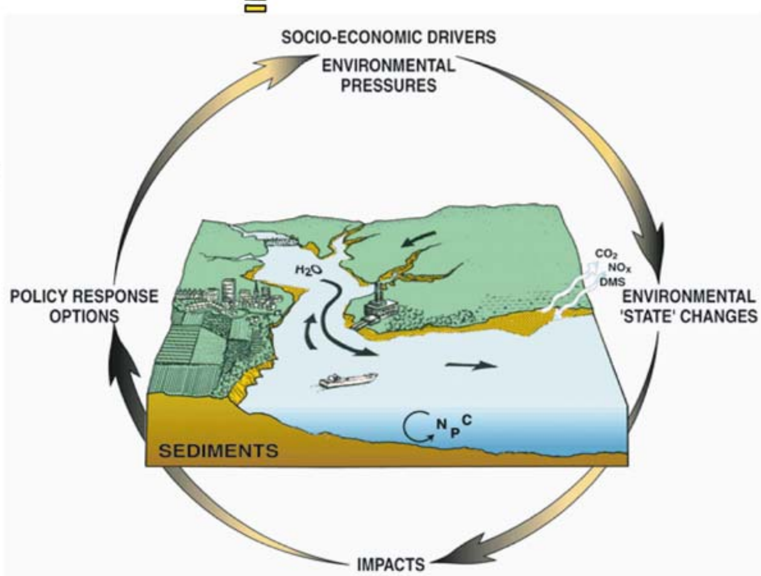


Fig. 4.5. LOICZ-Basins. Example of questions and upscaling assessment from South America (from Lacerda et al. 2002)

Text Box 4.2. The Caribbean

From Kjerfve et al. 2002

The Caribbean is an enclosed tropical sea covering 1943000 km^2 (Fig. TB4.2.1). The countries of the Caribbean region range from small, low islands to continental, mountainous lands with vast differences in rainfall patterns, climate, landform and land use. Humans have modified almost all of the Caribbean land for at least the past 500 years and only a few virgin forests remain. The coastal zone of the Caribbean supports more than 100 million people in more than 25 countries and territories with an anticipated population doubling time of 30 years at the current rate of growth. Intense housing, industrial and tourism developments compete for limited available space and attention from local governments and authorities.

The coastal environment consists of interlinked open marine and coastal ecosystems in a geographically diverse setting. Mangrove wetlands, seagrass beds and coral reefs are the dominant coastal habitats, each exhibiting high productivity and rich biological diversity. River drainage basins are relatively small for the most part because most of the countries are island states. However, the Magdalena River of Colombia, with a catchment of 257000 km^2, drains directly into the western Caribbean at Barranquilla, delivering inputs of freshwater of 228 $km^3\,yr^{-1}$ and sediment of 144×10^6 t yr^{-1}. Generally, however, in contrast to the larger basins of South America, impacts are characterised by a short time response to changes in land use and cover, i.e., basin development activities to coastal state changes. The buffering capacity is less effective in small river catchment systems than in larger catchments.

Sedimentation/erosion is the most significant issue for the region followed by pollution, eutrophication and salinisation, and a broad-scale loss of biodiversity (Table TB4.2.1). For ex-

Table TB4.2.1. The Caribbean. Links between coastal issues/impacts and land-based drivers; overview and qualitative ranking. (* Categories based on accumulated local and sub-regional information: 1, low; 10, high. Trend: ⇒ stable, ⇑ increasing)

Coastal impact/issues	Anthropogenic drivers	Category*	Trend expectations	Sub-regions particularly affected
Sedimentation (salinisation – here a minor concern)	Damming/ diversion	10	⇒/⇑	Magdalena River and El Dique Canal; Delta and lagoon complex (Cienaga Grande de Santa Marta)
Sedimentation	Deforestation	8	⇑	Magdalena River, Colombia; Gulf of Paria, Trinidad, Eastern Caribbean; Aroa-Yaracuy River, Golfo Triste, Venezuela; Sibun, Belize; Sarstoon and Motagua Basins, Guatemala; Chamalecon, Ulua, and Aguan Rivers, Honduras
Pollution/ eutrophication	Tourism	8	⇒/⇑	Cancun, Cozumel, and East Coast of Yucatan, Mexico; Roatan, Honduras; El Rosario Islands, Caribbean Coast of Colombia and El Dique Delta
Pollution/ eutrophication	Urbanisation and industry	7–8	⇑	Magdalena River, Colombia; Kingston Harbor, Jamaica; Aroa-Yaracuy River, Golfo Triste, Venezuela; Chetumal Bay, Mexico; Belize City; Manabique, Guatemala; Roatan, Honduras
Eutrophication/ pollution	Agriculture	6 (locally up to 9)	⇑	Magdalena River, Colombia; Gulf of Paria, Trinidad, Eastern Caribbean; Rio Cobre, Jamaica; La Estrella River, Costa Rica; Aroa-Yaracuy River; Golfo Triste, Venezuela; Sibun, Stann and Monkey Basins, Belize; Sarstoon and Motagua Basins, Guatemala; Chamalecon, Ulua, and Aguan Rivers, Honduras
Sedimentation	Navigation	8	⇑	Magdalena River mouth (Bocas de Ceniza)
Biodiversity loss and/or decreasing biological productivity	Various drivers: (urbanisation, industry, damming/diversion	8 (locally 10)	⇒/⇑	Aroa-Yaracuy River; Golfo Triste, Venezuela; Magdalena delta and lagoon complex (Cienaga Grande de Santa Marta mangrove system); Magdalena River-El Dique Canal and El Rosario Islands (coral reefs)
	Various drivers: (tourism defores-tation, agricul-ture, fishing)	4	⇑	Gulf of Paria, Trinidad, Eastern Caribbean; Kingston Harbor, Jamaica; La Estrella River/Cahuita Reef, Costa Rica

Text Box 4.2. *Continued*

ample, poor land-use practices, population growth and technological development have led to degradation of mangroves and coral reefs. Many drivers contribute to the generation of change and impacts, including (in order of importance): damming/diversion of rivers (particularly in the Magdalena subregion), deforestation, tourism (over a wide range of locations), urbanisation/industrialisation, agriculture and navigation. Land-use change and irrigation will generate growing pressure since many of the islands of the Caribbean suffer from low rainfall and thus lack of potable water. The response to coastal issues is usually hard engineering (coastal sea defences) rather than more environmentally sustainable soft engineering solutions.

Development is and will remain the major threat to river/island and coastal conservation and management in the Caribbean region. Biodiversity losses are a key concern. Similar to other tropical coastal ecosystems, the most important feature of the Caribbean is how interdependent the different components are, particularly in a downstream direction. For instance, mangrove forests generally benefit from increases in inorganic nutrients which the sediments have a high capacity to denitrify; one hectare of forest can probably process sustained inputs of 300 kg of N and 30 kg of P annually. In the Caribbean as elsewhere, mangrove forests are among the first coastal system to be destroyed. Seagrasses in the shallow sub-tidal zone are vulnerable to eutrophication; plankton-reducing light conditions and epiphytes covering the grass blades. The result is that seagrass beds decline, increasing nutrient flow to the reefs thereby stimulating massive algal growth that smothers the reefs. Virtually all of the coral reefs of the Caribbean region are either in critical condition (loss in 10–20 years) or threatened (loss in 20–40 years). Mangroves, seagrass beds and coral reefs, the three important and dominant coastal ecosystems in the Caribbean, need to be managed together in order to support efforts towards environmental and social sustainability in this fast growing economic region.

Numerous coastal and marine reserves and parks have been established, and many more are currently being created. These protected areas are likely to play a critical role in sustaining both productivity and marine biodiversity in the Caribbean, and thus contributing to the integrated coastal zone management of the region as a whole.

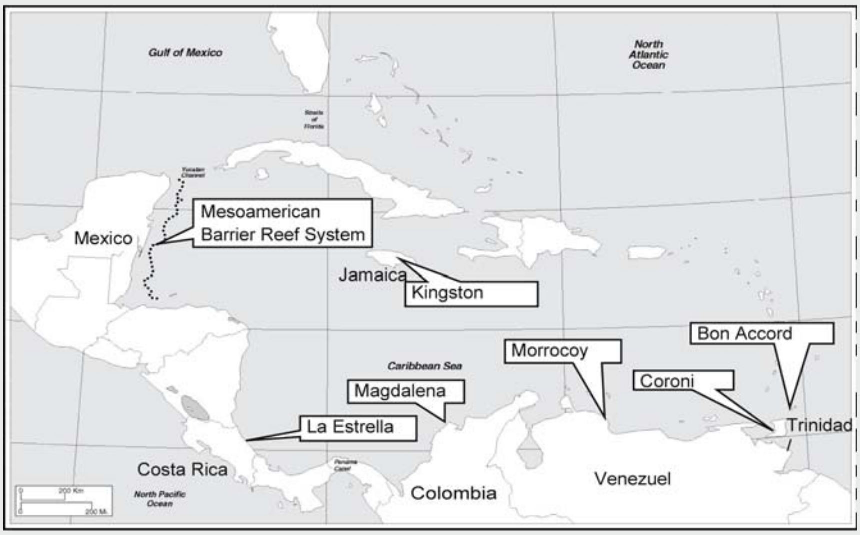


Fig. TB4.2.1. Caribbean. Case studies sites

Text Box 4.3. Oceania

From Morcom et al. 2002

Like other island-dominated regions, considerable parts of the broad area of Oceania (Fig. TB4.3.1) face serious environmental problems including widespread destruction of mangrove forests and coral reefs around population centres, urbanisation, overfishing, deforestation, soil erosion, misuse of pesticides, pollution of rivers and drinking water supplies, improper disposal of industrial and municipal wastes, and lack of sewage treatment facilities. The environmental and human impact of nuclear fallout from British, American, French and Soviet weapons testing programs still needs to be assessed. The paucity of published information, in particular on the cycling of water, sediment, nutrient, carbon and contaminant fluxes in the coastal zone of Oceania, has hampered attempts by LOICZ to assess nutrient fluxes in the region.

Polluted rivers and drinking water supplies are common in Oceania. Drivers/pressures are untreated municipal waste, urban sewage, agricultural runoff and mining (Table TB4.3.1). The last is most pronounced in the Fly River, Papua New Guinea, which carries levels of copper beyond threshold for sustained system functions; it was also impacted by several accidental spillages of toxins such as cyanide. In 1996 the extensive environmental damage resulted in US$ 320 million compensation in favour of the local communities to be used for pollution control and US$ 32 million to relocate whole villages. Other areas under mining pressure are New Caledonia and Guam.

Oceania has a chronic freshwater shortage; regionally water rationing has been imposed and locally water is routinely supplied for only one hour every second day. Urbanisation, domestic sewage and solid waste, agricultural wastes and industrial wastes all threaten the quality and supply of freshwater, in particular to low islands. These pressures are and will be exacerbated by climate change and future sea-level rise.

Coastal waters in the Oceania region are also polluted by industry. Industries such as fish canning, sugar milling, beer brewing and edible oils processing are significant regional pollutants of marine waters. Many hazardous and toxic wastes associated with

Text Box 4.3. *Continued*

medium-scale industrial bases in Fiji and Papua New Guinea are not well documented. However, a trend analysis expects industrial waste loading in Oceania to be increasing. These pressure/state change relationships raise substantial economic and public health issues in the region. For example, in Suva 95% of mangrove shellfish collected at eight sites was found to exceed World Health Organization limits of contamination for human consumption.

Another issue of high coastal relevance is sedimentation. Increased by intensifying land-use and cover change such as logging activities, urbanisation and rapid coastal development, mining, intensive agriculture and natural events, direct and indirect sediment effects on reefs and mangroves can be observed (e.g., around Suva, Fiji).

In summary, the amount of freshwater in Oceania is unlikely to increase and there is little evidence to suggest that the quality of polluted drinking water, rivers and coastal waters will be restored. There is potential for sewage, municipal and industrial wastes to be treated, which would directly affect fresh and coastal waters. However, the cost of building and maintaining such treatment facilities may be beyond many oceanic nations, dependencies and territories.

In response, pollution of fresh, coastal and marine waters is now recognised in Oceania, and the South Pacific Regional Environmental Programme (SPREP) Action Plan may provide an effective way forward with respect to environmental concerns.

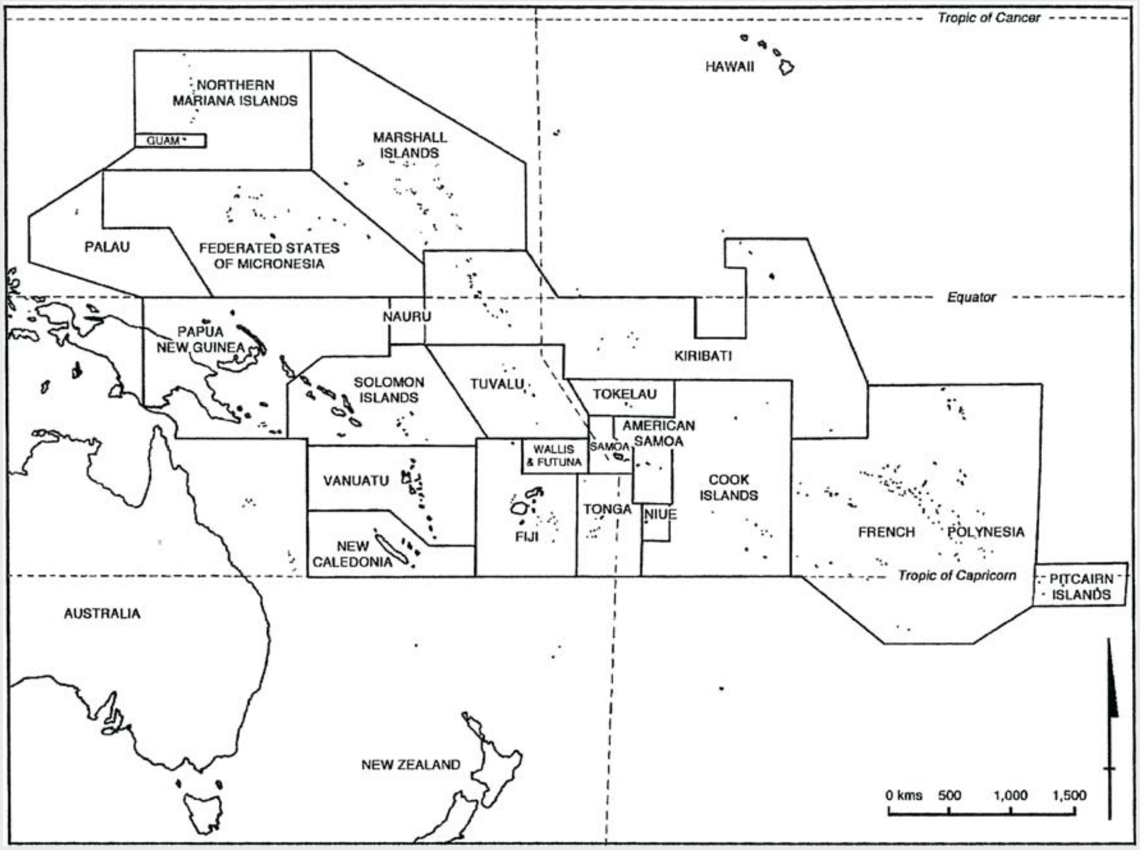


Fig. TB4.3.1. The Oceania region

4.2 South America

4.2.1 Overview of South American River Catchment-Coastal Zone Systems – Geography and Climate

The South American Atlantic coast is dominated by a few very large and many medium-sized river catchments and wetlands, all of which input nutrients that support the major part of the primary production and fisheries of the tropical and sub-tropical coasts of the sub-continent. These rivers discharge into the Atlantic to a relatively broad continental shelf (Kellogg and Mohriak 2001). Many of the medium-sized systems are visibly altered through human activities. Consequently, land-use and cover change, pollution and water diversion, which are drivers changing horizontal mass transport, are likely to cause stronger state changes and to generate acute coastal impacts when associated with these medium-sized catchments than, for instance, those associated with the Amazon. In contrast, along the Pacific coast of the sub-continent, characteristically small catchments discharge to a relatively narrow continental shelf with strong interac-

Text Box 4.3. *Continued*

Table TB4.3.1. Oceania. Links between coastal issues/impacts and land-based drivers; overview and qualitative ranking. (* Categories based on accumulated local and sub-regional information: 1, low; 10, high. Trend: ⇒ stable, ⇑ increasing)

Coastal impact/issues	Anthropogenic drivers	Category*	Trend expectations	Location
Pollution/ sedimentation/ erosion	Mining	10	?	Fly, Ok Tedi and Jaba Rivers, Papua Niew Guinea (PNG), Rivers in New Caledonia
Biodiversity loss/ decrease of biological productivity	Various drivers	10	⇑	Fly and Jaba Rivers, PNG; Rivers in southern New Caledonia; Suva-Fiji coastal waters
Sedimentation/ erosion Eutrophication	Deforestation	9	⇑	Rivers in Fiji; Rivers in southern New Caledonia and Solomon Islands
Eutrophication/ sedimentation/ Erosion/pollution	Urbanisation	8	⇑ ⇒	Rivers of Fiji, (Rewa, Vatuvaga River, Suva harbour – sewage); Tarawa lagoon, Kiribati –sewage, erosion; Nubukulou Creek – electricity and septic tanks); Oraniqio River – Fiji – sedimentation
Eutrophication/ pollution Sedimentation/ erosion	Agriculture	7	⇑	Rewa River, Fiji, other Streams in Fiji (pesticides); Waimanu River Fiji

tions with open ocean waters (Kellogg and Mohriak 2001). Therefore, the catchment basin effects on the receiving coastal waters differ between Pacific and Atlantic systems.

For both coasts a second sub-regional classification applies encompassing the wide range of climatic conditions from tropical to sub-Antarctic patterns. Desert-like regions along the Peruvian and Chilean coastline are replaced by humid areas with considerable annual rainfall further south in Chile, and north in Ecuador and Colombia. The northeast and central eastern parts of the Atlantic coast are tropical or sub-tropical, but arid in the northeast and humid in the east. The southern Atlantic coast exhibits more arid conditions with sparse vegetation.

Eight sub-regional divisions (Fig. 4.6a) and characteristic rivers (Fig. 4.6b) were selected as representative of South American catchments (Text Box 4.4).

4.2.2 Assessment of Land-based Drivers, Pressures and Coastal Impacts

4.2.2.1 *Drivers and Pressures*

Catchment basin activities have considerable influence on the environmental state of many South American coastal areas. Anthropogenic pressures are also characterised by two major features: urbanisation and mega-cities either affect the coastal waters and estuaries directly (e.g., Buenos Aires and Rio de Janeiro) or contribute to coastal change indirectly through the catchments that carry their urban waste-load (e.g., Caracas and São Paulo). Areas such as Patagonia and the northeast of Brazil have low population density and runoff, so that water quality is relatively un-impacted. Economically driven changes in land use affect large remote regions, for example, through deforestation that has a visible influence on the geomorphology of catchments as well as on the hydrological conditions. These pressures, although they appear insignificant in terms of immediate and visible coastal change (e.g., deforestation in the Amazon basin), may have strong potential for significant future impacts. There is an array of locally dominating drivers and pressures that tend to characterise the sub-regions.

4.2.2.2 *Coastal Issues – State Changes and Impacts*

The principal and most extensive coastal issues for South America are pollution, eutrophication, and the changing erosion/sedimentation equilibrium, although other issues may be more important at the site-specific level (Table 4.1). These pressures have already caused measurable impacts on South America's coastal zone, resulting in varying degrees of displacement from a baseline state in many ecosystems.

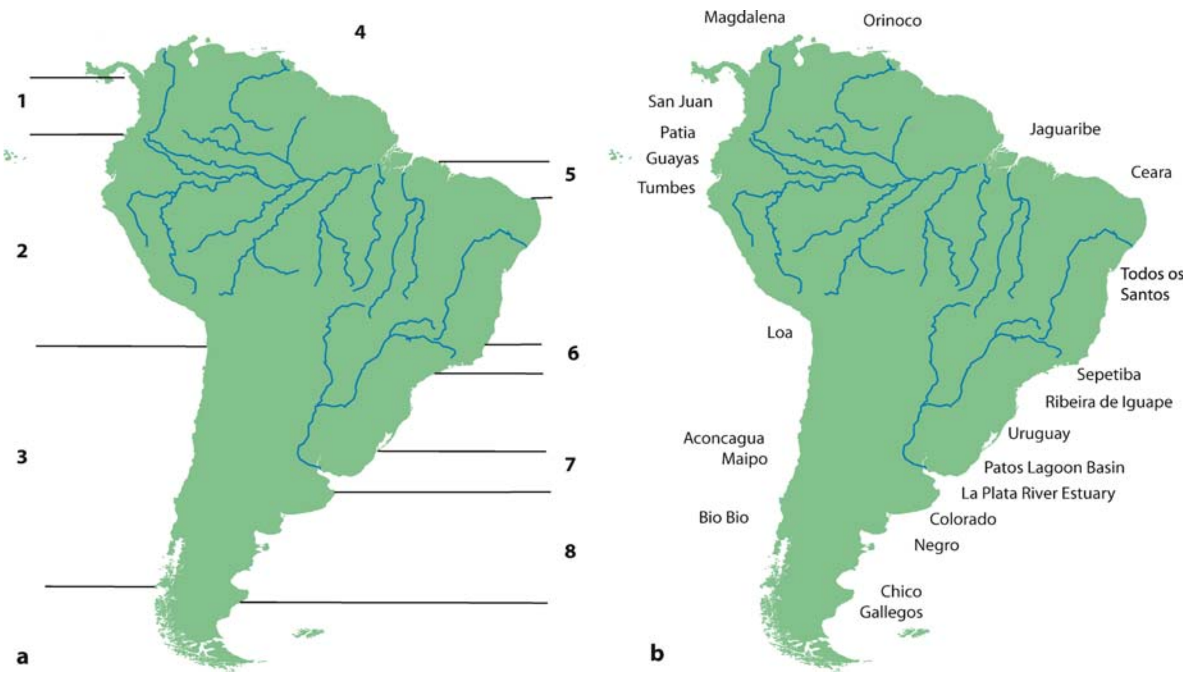


Fig. 4.6. South America. **a** The sub-regions identified in the South American Basins (SAmBas) study; **b** a selection of river catchment-coast systems evaluated (from Lacerda et al. 2002)

Pollution

Pollution is considered here as both the introduction of human-made substances into the aquatic environment that are harmful to human or animal life and health (e.g., pesticides, hydrocarbons, PCBs), and the increase to toxic levels of naturally-occurring elements (i.e., heavy metals). Continental inputs of trace metals, oil, oil derivatives and xenobiotics are rapidly increasing in parallel with economic development of most countries of the subcontinent. Diverse areas of the coastline, especially protected shores, are continually under pressure. Such areas in South America harbour over 2 million hectares of highly productive mangroves and wetlands that are nursery grounds for coastal fisheries. These key ecosystems are exposed to contaminants transported by rivers, and which can be conveyed through food chains to the human population.

Most pollutant inputs involve heavy metals from industrialisation and agriculture along river catchments. Copper contamination from pesticides used in agriculture is affecting the Negro River and southern Brazil. Even in relatively undisturbed environments, such as the rivers of Patagonia and north-eastern Brazil, heavy metal concentrations are generally much higher than local background values. As with nutrients, the high flushing rate to the open ocean due to coastal upwelling results in a large dilution of pollutant concentrations.

Atmospheric deposition of pollutants in basins transported by runoff also contributes significantly to increasing heavy metal concentrations in coastal seas. This is particularly important for metals such as lead and mercury, whose cycles include a significant atmospheric component; even relatively remote areas show abnormal concentrations of these two metals. Accelerated land-use changes in coastal basins also contribute to the re-mobilisation of deposited pollutants on soils.

Oil exploration and production in many river basins in South America is a key issue. Oil exploration in the Andes results in frequent oil spills introducing elevated levels of heavy metals that eventually affect the coastal zone.

Mining, although less important to catchment-coast interactions, may be significant in some regions. For example, in the Gallegos River, coal mining leads to increased lead concentration. Small-scale gold-mining is carried out in basin systems generally far from the coast close to the Andes Cordilleras, but mercury is transported from these inland sources to the coastal zone where it enters the food-chains.

Organic micro-pollutants are not significant contaminants of coastal waters in South America, but at some sites they show relatively high concentrations; for example, in the Esmeraldas River in Ecuador, the La Plata River estuary and some sites along the Patagonia coast.

Eutrophication

Urban and agricultural wastes released to the coast are raising special concerns in terms of impact on coastal waters. Eutrophication and coastal erosion rank as the

Text Box 4.4. South America: catchment sub-regions

From Lacerda et al. (2002)

Sub-region 1. North tropical Pacific coast, Columbia, Ecuador: the high rainfall Pacific coast of Colombia and Ecuador (latitudes 7° N to 0° S), rivers with small drainage basins but with large water and sediment discharges and high sediment yields. Typical rivers are the San Juan and Patia rivers in Colombia, with catchment areas of only 14 km^2 and sediment yields in the range of 1 000 $t\,km^{-2}\,yr^{-1}$, and the Esmeraldas and Chone rivers in Ecuador. Average annual rainfall for this sub-region is 5 900 mm. About 260 km^3 fresh-water is discharged annually into the Pacific Ocean, with a sediment load of nearly $31 \times 10^6\ t\,yr^{-1}$).

Sub-region 2. Central Pacific coast, Ecuador, Peru, northern Chile: the driest coast of South America, from the Gulf of Guayaquil in Ecuador to northern Chile, including the entire Peruvian littoral (latitudes 0° S to 30° S). Most coastal features are dominated by open ocean phenomena and are greatly affected by El Niño events. Although river inputs may be important sources of nutrients to the coastal region, at least for the Gulf of Guayaquil, most of the coastal productivity and fisheries are dependent on oceanic upwelling. Typical rivers are the Guayas River in Ecuador, the Tumbes and Chira rivers in Peru and the BioBio River in Chile, all of which have small basins, large water and sediment discharges and high sediment yield. The Gulf of Guayaquil has the highest rates of mangrove deforestation and conversion to aquaculture in the world, having lost about 80% of its original area (3 973 ha to 785 ha between 1969 and 1991). This has caused large changes in geomorphology and basin land-use with direct effects on the coast.

Sub-region 3. Southern Pacific Coast, Chile: the southernmost area along the Pacific coast between latitudes 30° S and 42° S, the south-central Chilean littoral, with a temperate climate. Exposed sandy beaches with varying morphodynamics alternate with intertidal sand flats at the mouths of rivers. Small rivers with large sediment yields and strongly seasonal flows dominate water and sediment transport. Strong interaction between coastal and open ocean waters results in large dilution of continental material after it reaches the coast.

Sub-region 4. Caribbean to north-western Brazilian tropical Atlantic coast: the northernmost area including the Magdalena River delta, a complex lagoon-deltaic system (latitudes 10–12° N), which is the major contributor of fresh-water and continental sediments to the Caribbean Sea. The lower basin has witnessed great changes since colonial times, with major water diversion works and artificial canals changing the position of major river output to the Caribbean Sea. The Magdalena River discharges 228 km^3 of water and 144×10^6 tonnes of sediment annually into the Caribbean. Water and sediment discharges have great environmental and economic impacts on the adjacent coastal ecosystems, particularly from high sedimentation rates in Cartagena Bay and siltation on coral reefs of the El Rosario Islands to the south-east.

Sub-region 5. North-eastern Brazil sub-tropical Atlantic coast: the extensive oligotrophic north-eastern coast of Brazil (latitudes 3–12° S), where small to medium, highly seasonal rivers contribute almost all the nutrients for coastal primary production and fisheries. Most of the coastline runs parallel to the Equator, where constant strong winds drive immense amounts of sands to the coast, creating large dune-fields that continuously change the coastal geomorphology. The semi-arid nature of the regional climate has resulted in intense impoundment of waterways, mostly for irrigated agriculture and urban use. This has led to an extreme reduction of freshwater and fluvial sediment load to the ocean and generalised erosion along the coastal region.

Sub-region 6. Central Brazilian Atlantic coast, Guanabara and Sepitiba Bay: the south-eastern Brazilian coast (latitudes 20–30° S), the most industrialised and urbanised part of South America. The climate is tropical humid with abundant rains year-round and annual rainfall of 1 200 to 2 600 mm. Several small rivers with huge event-controlled discharges transport large volumes of sediments and pollutants to the coastal seas. Environmental pressures along this coast are enormous, mostly associated with unplanned urban and industrial development concentrated along very narrow coastal plains that house about 60 million people and the largest industrial parks and ports of the subcontinent.

Sub-region 7. Wider La Plata Atlantic coast, south-eastern Brazil, Uruguay, Argentina: the southern coast of Brazil (latitudes 30–38° S), and the region of influence of the Rio de la Plata estuary, mostly in a warm temperate climatic zone. This huge coastal plain is drained by three large rivers, the Uruguay, Paraná and Guaíba, that discharge into the Patos Lagoon, the largest coastal lagoon in the world. The Argentine and Uruguayan coasts of the Rio de la Plata contain the highest concentration of human population and industrial activities south of the São Paulo-Rio de Janeiro metropolitan areas. Agriculture and husbandry are the major activities of these large river basins. The coastal features and problems shared by the three countries pose a challenge for integrated coastal zone management on a multi-national level.

Sub-region 8. South-eastern Atlantic coast, Argentina, Patagonia: the Patagonia littoral in Argentina, (latitudes 38–52° S), with a temperate climate and an annual rainfall of less than 800 mm. The sub-region is characterised by long coastal-plain rivers that are still relatively undisturbed. Major rivers are the Negro, Chubut, Santa Cruz and Colorado with basin areas of 95, 30, 25 and $22 \times 10^3\ km^2$, respectively. However, water discharge is relatively small, less than 2 000 m^3 per year. Extensive livestock breeding (particularly of sheep) and increasing agricultural activities are threatening many coastal sites of high ecological value to migrating species.

most important impacts on both coasts of South America. In most cases, direct links can be made to increasing population density and urbanisation of coastal catchments, even in regions of low population density, such as Patagonia and north-eastern Brazil.

The coasts of south-eastern Brazil and Buenos Aires Province are probably the regions most affected by eutrophication, reflecting the high concentrations of population and industries along major drainage rivers. Nutrient levels measured at nearly 200 stations along rivers draining to the metropolitan area of Rio de Janeiro showed concentrations one to three orders of magnitude higher than background. Elevated levels of coliforms (500 colis (Número Mais Provável (NMP)) 100 $m\,l^{-1}$) derived from river catchments can be measured in open oceanic waters off the beaches of the region. Even along the sparsely populated Uruguayan coast, low oxygen and high nitrogen concentrations have been observed.

Toxic algal blooms have increased in frequency along the eastern coast of Uruguay, the coastline of metropolitan Fortaleza in north-eastern Brazil and the Patagonian coast of Argentina, probably associated with an increase in freshwater inflow and sewage discharge. Along the Patagonian coast this may have increasing effects on important mussel banks and mariculture sites. In the spring of 1980, the human health dimension of increased riverine nutrient loads became apparent there when a large algal bloom caused human deaths from consumption of mussels contaminated by *Alexandrium* sp.

In Colombia, bacteria reaching coastal waters from sewage discharged into river basins has contaminated oyster banks. Non-toxic algal blooms have also been causing fish kills along the Caribbean coast of Colombia due to localized depletion of oxygen.

In some Venezuelan Caribbean islands, there is evidence of a growing frequency of *Ciguatera* blooms causing poisoning among humans, resulting from higher nutrient inputs to coastal areas. Periodic red tides contaminate mussels and oysters in the region. However, there is currently no evidence that these blooms are associated with inputs from catchment basins.

Along the Pacific coast of South America, eutrophication is an important issue. However, it seems to be more restricted and intense than on the Atlantic coast. Only in the Gulf of Guayaquil and along part of the northern Ecuadorian coast are nutrient levels high. To the south, the intense exchange between coastal and oceanic waters probably decreases the impact of augmented nutrient loads from rivers.

Coastal Geomorphology (Erosion, Siltation)

Diversions and damming of waterways are seriously affecting the erosion-accretion equilibrium of large stretches of the South American coastline. Examples can be found along the north-eastern Brazil coast and the Caribbean coast of Colombia and Venezuela.

Changing river sediment load alters the sedimentation-erosion equilibrium within an estuary or delta (also see Chap. 2). Coarse-grained bed load (> 60 µm) normally represents 10% or less of the total sediment discharge delivered to the coastal zone. Hence, it is assumed that a decrease of about 5% of the total sediment flux represents the critical threshold beyond which the coastal system is likely to show evidence of significant deterioration (coastal erosion). This level of change results in mangrove siltation (e.g., along the river estuaries in north-eastern Brazil), severe erosion of mangroves (e.g., in the Paraíba do Sul River delta, south-eastern Brazil) and sandy beaches (e.g., along the coasts of Buenos Aires Province in Argentina and in north-eastern Brazil).

Deforestation of river catchments facilitates soil erosion changing sediment quantity and quality resulting in increasing siltation of the coastal zone. The mouth of the Magdalena River in Colombia, where a major port is located, needs continuous dredging to prevent sedimentation. Disposal of dredged materials has affected adjacent sandy beaches, coral reefs and mangroves that cannot keep up with the increased sediment load. Evidence from deforestation-caused soil erosion has shown that long-lasting contaminants, such as heavy metals, may also be remobilised, increasing the contamination threat in coastal areas.

In semi-arid Argentinean Patagonia, scarce vegetation and increased livestock (sheep) pressure have resulted in considerable erosion and a heavy load of suspended matter carried to the ocean by the Chico River.

Biodiversity and Harvestable Resources

Loss of habitats and species is widespread along most of the sub-continent's coastline. These effects are mostly measured as significant losses of fisheries. Annual catches have been historically monitored at many sites and can provide reliable "critical threshold estimates" for this parameter. Extreme cases are the 90% reduction of commercial fisheries during the past 20 years at the Magdalena River delta and the 90% decline of viviparous shark catches at the Patos Lagoon estuary. Apart from fisheries, extensive mangrove areas in Ecuador and Colombia and salt marsh areas in southern Brazil have been lost.

4.2.3 State Changes, Impacts and Future Trends

Since impacts on the coastal zone promoted by the different forcing functions along the water continuum of the catchment may appear across different time scales, temporal change and variability represent crucial information for decision-making processes. Tables 4.1 and 4.2 show the ranked importance of impacts on coastal areas by catchment activities and their trend expectations.

The Atlantic coast of South America is more sensitive to impacts from catchment basin activities than the Pacific coast. The Atlantic border harbours the majority of the population and economic activities of South America, and over 90% of the South American drainage discharges into the Atlantic and Caribbean (Kellog and Mahiuk 2001). Oceanographic conditions and continental shelf geology also enhance longer residence times of sediments, water, and natural and anthropogenic substances from continental land sources whereas along the Pacific coast strong flushing results in rapid dilution of continental input into the open ocean.

Major impacts (ranking higher than 6) along the Atlantic coast include pollution due to industrialisation, eutrophication due to urbanisation, erosion and sedimentation due to deforestation and damming, and nutrient depletion due to damming. Along the Pacific coast, erosion due to deforestation and navigation and sedimentation due to deforestation are the major impacts and drivers. Trends indicate that future impacts are likely to increase in severity if economic growth continues and accelerates. It is important to note, however, that the local site-specific situation may differ from this longer term aggregate forecast. Therefore, reference should be made to the catchment level assessments (Lacerda et al. 2002) to gain a view of the relative importance of the impact/issue and associated driver at that local scale.

The qualitative ranking of major land-based activities, the present status of their effects on the coastal zone of South America and trend expectations derived by the group of experts are summarised in Table 4.2. On sub-continental scale eutrophication, pollution and changes in coastal geomorphology (erosion) were ascribed as the most important coastal impacts. Databases on nutrients and sediments are scarce or not easily accessible, a situation that needs improvement for management as well as assessment efforts. An overview on the biogeochemical characteristics of South American estuaries and lagoons has been produced based on available information and applying the LOICZ budgeting methods (Smith et al. 2000). A significant information gap exists for small rivers, in particular for those on the Pacific coast. An expert workshop elicited general agreement that small and medium-sized rivers are responsible for the majority of coastal waters' productivity, coastal amenities and coastal change especially along the Atlantic coast.

Table 4.1.
South America. Links between coastal issues/impacts and land-based drivers; overview and qualitative ranking at regional/sub-continental scale. (Category: 1 = low; 10 = high. Trend: ⇒ stable, ⇑ increasing, n.o. = not observed)

Atlantic Coast				Pacific Coast	
Coastal impact/issues	Driver	Category	Trend expectation	Category	Trend expectation
Pollution	Industrialisation	9	⇑	2	⇑
	Navigation	7	⇑	5	⇑
	Agriculture	5–6	⇑	?	⇑
	Urbanisation	6	⇑	5	⇑
Eutrophication	Urbanisation	8	⇑	5	⇑
	Agriculture	4–5	⇑	2	⇑
	Industrialisation	3	⇑	2	⇑
Sedimentation	Damming	8	⇑	n.o	n.o.
	Deforestation	7–8	⇑	6–7	⇒
	Navigation	6	⇑	n.o.	n.o
	Agriculture	4	⇒/⇑	2	⇒
Erosion	Deforestation	7	⇒/⇑	6	⇒
	Damming	6–7	⇒/⇑	1	⇒
	Navigation	1	⇒	7	⇑
Nutrient depletion	Damming	8	⇑	n.o.	n.o.
Salinisation	Damming	4	⇑	n.o	n.o.
Loss of biodiversity	Fisheries	4–6	?	2	⇑

Table 4.2. South America. Major activities, present status and trends affecting the coastal zone. (Trend: ⇒ stable, ⇑ increasing, ⇓ decreasing; *numerals* refer to sub-regions described in Text Box 4.4, Fig. 4.6a)

Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations	Sub-regions particularly affected
Urbanisation	Eutrophication	Major	⇑	1,2,3,4,6,7
Damming/diversion	Erosion/sedimentation	Major	⇑	2,4,5,7,8
Deforestation	Erosion/sedimentation	Medium	⇑	1,2,6,7,8
Industrialisation	Pollution	Medium	⇑	1,2,6,7
Agriculture	Eutrophication/pollution	Medium	⇑	2,4,7,8
Aquaculture	Eutrophication	Minor	⇑	1,2,5
Navigation	Erosion/sedimentation	Minor	⇒	2,4,7
Fisheries	Loss of biodiversity	Minor	⇒	5,6,7
Tourism	Erosion/eutrophication	Minor	⇑	5,6
Mining	Erosion/pollution	Minor	⇓	5,8

Sub-region 1 · Northern Tropical Pacific Coast, Colombia/ Ecuador

Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Eutrophication	Major	⇑
Industrialisation	Pollution	Medium	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Aquaculture	Eutrophication	Minor	⇑

Sub-region 2 · Central Pacific Coast, Ecuador/ Peru/ N. Chile

Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Eutrophication	Major	⇑
Damming/ diversion	Erosion/ sedimentation	Major	⇑
Industrialisation	Pollution	Medium	⇑
Agriculture	Eutrophication/ pollution	Medium	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Aquaculture	Eutrophication	Minor	⇑
Navigation	Erosion/ sedimentation	Minor	⇒

Sub-region 3 · Southern Pacific Coast, Chile

Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Eutrophication	Major	⇑

Sub-region 4 · Caribbean to NW Brazilian tropical Atlantic Coast

Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Eutrophication	Major	⇑
Damming/ diversion	Erosion/ sedimentation	Major	⇑
Agriculture	Eutrophication/ pollution	Medium	⇑
Navigation	Erosion/ sedimentation	Minor	⇒

Sub-region 5 · North East Brazilian sub-tropical Atlantic Coast

Driver	Major coastal impact	Present pressure status	Trend expectation
Damming/ diversion	Erosion/ sedimentation	Major	⇑
Aquaculture	Eutrophication	Minor	⇑
Tourism	Erosion/ eutrophication	Minor	⇑
Fisheries	Loss of biodiversity	Minor	⇒
Mining	Erosion/ pollution	Minor	⇓

Sub-region 6 · Central Brazilian Atlantic Coast, Guanabara & Sepetiba Bay

Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Erosion/ sedimentation	Major	⇑
Industrialisation	Pollution	Medium	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Tourism	Erosion/ eutrophication	Minor	⇑
Fisheries	Loss of biodiversity	Minor	⇒

Sub-region 7 · Wider La Plata Atlantic Coast, SE Brazil, Uruguay, Argentina

Driver	Major coastal impact	Present pressure status	Trend expectation
Urbanisation	Eutrophication	Major	⇑
Damming/ diversion	Erosion/ sedimentation	Major	⇑
Industrialisation	Pollution	Medium	⇑
Agriculture	Eutrophication/ pollution	Medium	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Navigation	Erosion/ sedimentation	Minor	⇒
Fisheries	Loss of biodiversity	Minor	⇒

Sub-region 8 · South East Atlantic Coast, Argentina/ Patagonia

Driver	Major coastal impact	Present pressure status	Trend expectation
Damming/ diversion	Erosion/ sedimentation	Major	⇑
Agriculture	Eutrophication/ pollution	Medium	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Mining	Erosion/ pollution	Minor	⇓

Fig. 4.7. South America. Sub-regional synthesis and typology of river catchment–coast interactions

Table 4.3. South America. Priority driver/pressure features by country and corresponding "hot spots"

Country	Driver/Pressure	Hot spots	Available information
Colombia	Pollution (generated by urbanization industry, mining); Deforestation (generated by agriculture); Diversion of river discharges	Rio Magdalena; Cartagena Lagoon (to be opened to the Caribbean)	Nutrient and sediment discharges and concentrations are available for the Magdalena River back to the 1970s, but refer only to the delta and the river
Venezuela	Industrial liquid discharges; Oil exploration and extraction; Livestock land use; Sewage (prevention still possible); Agriculture	Orinoco Delta; Neveri River; Catatumbo River; Maracaibo Lake; Tuy River; Limon and Aroa rivers; Unare/ Chama rivers	Information available in comprehensive reviews, including nutrient and sediment discharges
Argentina	Pollution (generated by urbanisation and industry); Erosion or siltation (due to land use change); Oil spills (upstream)	Rosario and Buenos Aires Province (due to transboundary transport from Brazil through the Paraná River); Patagonia	Overview reports on the Parana-La Plata Rivers[a] Bibliography from various case studies in small Patagonian rivers
Brazil	Damming; Diversion; Irrigation; Agriculture (enhanced nutrient loads); Deforestation; Navigation	Jaguaribe River, NE coast, Ceará State; SE coast from the São Francisco River to Bay of Paranaguá; The Paraíba do Sul River-Sepetiba Bay, Rio de Janeiro	Major bibliography sources reviewed and published, addressing major issues on Integrated Coastal Zone Management. The national Water Agency (ANEEL), monitors water fluxes in major rivers. Historical data available on the internet
Uruguay	Navigation (timber transport); Agriculture (more irrigated rice paddies); Irrigation	Parana River[a]; Uruguay River; La Plata River	GEF project report[b]

[a] The Parana-La Plata Basin has been the subject of overviews promoted under the MERCOSUR agreement.
[b] Ongoing GEF project in the La Plata Basin.

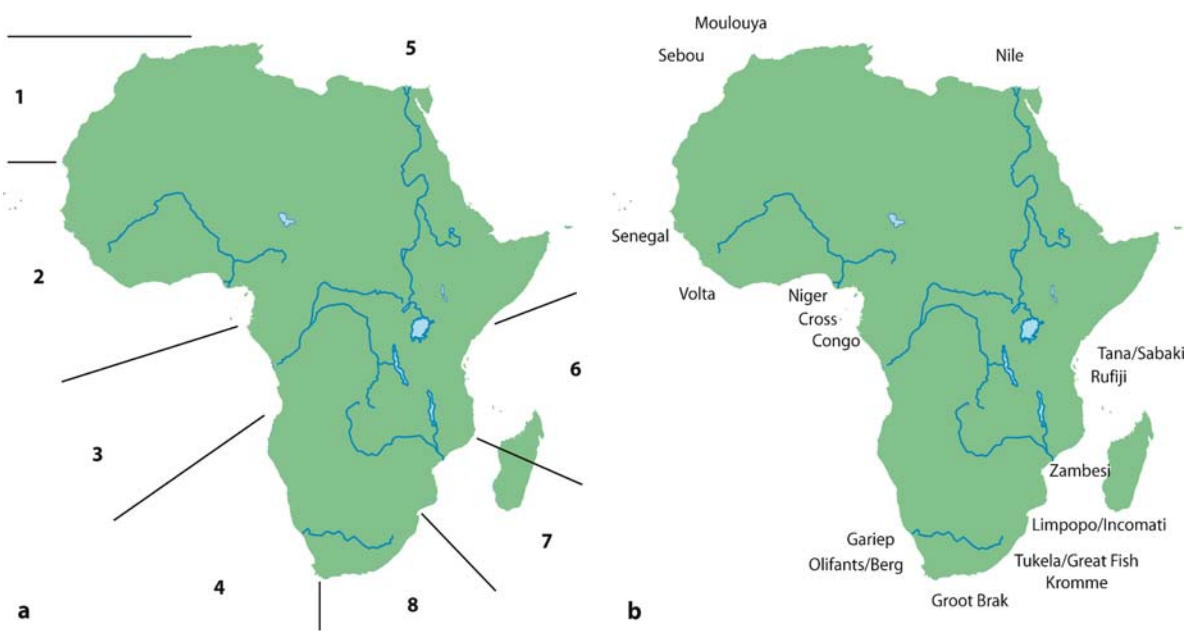


Fig. 4.8. Africa. **a** The sub-regions identified in the AfriBasins study; **b** a selection of river catchment-coast systems evaluated (from Arthurton et al. 2002)

4.2.4 Conclusions – South America

River basins of all sizes are, or are becoming, increasingly affected in particular by diversion of waters and/or damming for energy generation and/or irrigation purposes, basin deforestation and pollution from agriculture, urban and industrial effluents. Figure 4.7 is a sub-regional synthesis of main river catchment-coastal change issues, and provides an expert judgement-based ranking and trend analysis.

A number of case studies, from across the South American sub-continent are summarised in Table 4.3 and address key issues and scales that occur at the land-sea interface. An overall evaluation of the data in Table 4.3 supports the conclusion that across South America issues of water quality followed by a series of sediment-related issues and aspects driven by demands for water resource availability are the most important.

4.3 Africa

4.3.1 Overview of African River Catchment-Coastal Zone Systems – Geography and Climate

The environmental and socio-economic issues of Africa's coastal zone are influenced by both natural and anthropogenic marine-related pressures, such as relative sea-level rise which exacerbates coastal erosion and flooding around Lagos in Nigeria. The coastal zone is also directly influenced by the pressures of human activities, notably urban and industrial growth causing pollution (e.g., Alexandria in Egypt) and eutrophication (e.g., Saldanha Bay in the Western Cape). Around much of Africa, however, many of the coastal issues are linked to human activities and climatic variability that are far away in the continental hinterland. Such continental pressures have altered the nature of the drainage through the river systems – large and small – impeding the flow of freshwater, transported sediment and organic matter. They have also affected the quality of the water, mainly through the addition of nutrients and pollutants from domestic sewage and industrial and agricultural chemicals.

On the basis of geomorphic and climatic characteristics, eight sub-regions were evaluated (Fig. 4.8a, Text Box 4.5) within which representative catchments were chosen for assessment (Fig. 4.8b; Arthurton et al. 2002). The various sub-regions differ widely not only in the biophysical nature of their catchments but also in the availability and quality of existing data relating to their material fluxes. The catchments in South West and South East Africa have generally been well-studied especially over the last few decades and there exists an abundance of accessible high-quality monitoring data, both terrestrial and marine. Data for the Congo, by contrast, is sparse – a matter of concern in view of the obvious importance of such a large catchment in a regional synthesis of river catchment-to-coastal sea fluxes.

4.3.2 Assessment of Land-based Drivers, Pressures and Coastal Impacts

All of Africa's largest river basins – Niger, Congo, Nile and Zambezi – are included in the assessment, as are the important trans-boundary basins of the Senegal, Volta, Cross and Gariep rivers on the west coast and the Limpopo and Incomati on the east coast. Representative medium and small basins have also been assessed, including:

- the Sebou and Moulouya rivers in Morocco
- the Olifants and Berg rivers (west of the Cape of Good Hope) in South Africa,
- the Tana and Sabaki rivers in Kenya,
- the Rufiji in Tanzania, and
- the Thukela, Great Fish, Kromme and Groot Brak in South Africa east of the Cape.

4.3.2.1 *Drivers and Pressures*

Apart from climate change, the principal internal drivers of environmental change within African catchments are agricultural development, urbanisation, and their related activities – deforestation, damming and industrialisation (Table 4.4, Fig. 4.9; UNEP 2002a). Forest clearance and the general reduction in vegetation cover are consequences of agricultural expansion into marginal land, fuel-wood gathering and rapidly growing urban sprawl (e.g., around Nairobi and Johannesburg). Damming, water diversion and groundwater extraction are practices that have increased significantly in Africa during the last 50 years, particularly in South Africa, in response to development demands for agricultural irrigation, freshwater supply (particularly to fast-growing urban areas) and hydroelectric power (World Commission on Dams 2000).

All of these land-based human activities within Africa have produced substantial socio-economic benefits at local to regional scales. They have also resulted in considerable negative impacts, both socio-economic (e.g., the disruption of communities and their livelihoods) and environmental (e.g., the alteration of natural flooding regimes, the degradation of agricultural land by increased soil erosion, the destruction of habitats and the loss of biodiversity). The pressures exerted by these activities

Text Box 4.5. Africa: catchment sub-regions

From Arthurton et al. (2002)

Sub-region 1. North West Africa: relatively arid, medium basins with seasonal runoff. North West Africa is characterised by young mountains and numerous medium and small drainage basins with strong slopes, while the alluvial plains are few and of limited extent. River runoff and precipitation are irregular and may be high. Poorly vegetated steep slopes are prone to surface runoff resulting in soil erosion and high levels of fluvial suspended sediment transport – probably among the highest in Africa. The Sebou and Moulouya catchments (located in Morocco) are representative of the medium drainage basins that characterise the semi-arid Maghreb area. Many large dams have been built over recent decades. The resulting sediment entrapment has not only reduced the reservoir capacity, but has also become a principal cause of coastal erosion. The main sources of coastal eutrophication and pollution are untreated domestic and industrial wastewater and fertilisers. Most urban sewage is discharged without treatment. Human health issues also arise from the discharge of untreated sewage (related to urbanisation), while loss of biodiversity (or biological functioning) is seen as a complex interplay of all the principal drivers.

Sub-region 2. West Africa: featuring large trans-boundary basins (Niger, Volta, Senegal) including the medium-sized basin of the Cross River. Coastal erosion is a problem in all catchments, with critical thresholds exceeded in the Volta and Niger. Damming, deforestation and agriculture all contribute, with damming the prime cause in the Volta. Coastal sedimentation is a common issue, especially at the mouth of the Senegal River. Algal blooms are a manifestation of eutrophication, particularly in the Volta and Niger, with urbanisation (or human settlement) and, to a lesser extent, agriculture the principal drivers. Oil-related pollution is an important issue in the Cross River basin, while aquatic weeds, such as *Nypa* palm, infest all catchments. Critical thresholds for the loss of biological functioning have been exceeded in the Volta and Niger and especially in the Senegal. Human health issues, including the incidence of water-related diseases attributed to urbanisation, have been reported in all catchments, with critical thresholds being exceeded in the Volta and Senegal.

Sub-region 3. Congo: the second largest river in the world on the basis of annual flow, extending over a distance of 4700 km from Lake Tanganyika to the Atlantic Ocean. The dominant characteristic of the Congo River is the remarkable regularity of its regime. The lower reaches of the basin (i.e., below Kinshasa and Brazzaville, some 300 km upstream) are free of major urban and industrial developments. Near the coast human activities involve fishing, gathering medicinal plants and subsistence cropping. The loss of habitat and biodiversity as a consequence of mangrove use for fuel wood is a major issue.

Sub-region 4. South West Africa (Namibia to Cape): mostly dominated by the upwelling system of the Benguela current; cool and temperate small (Berg) and medium (Olifants) catchments in the south and an arid large catchment (Gariep, formerly Orange) in the north. The major perennial river basins that influence the coastal zone include the Kunene, the Gariep, the Olifants and the Berg. Urban nodes, which also have a significant influence on the coastal zone, include Walvis Bay, Saldanha Bay, Table Bay and False Bay. The Gariep estuary is one of southern Africa's most important coastal wetlands; the dynamics of its deltaic mouth are affected by upstream impoundments and associated water-use practices. Human activities in the Olifants catchment appear to have a limited impact on its estuary and coastal zone, although damming and agriculture have led to a reduction of fresh-water inflow. In the Berg River, flow is very seasonal and the high concentration of dissolved inorganic nitrogen in the winter (wet season) is attributed largely to fertiliser from agricultural runoff. Urban and industrial nodes are associated with the progressive deterioration of water quality. Eutrophication attributed to industrial development around Saldanha Bay is of considerable concern. Of the urban node embayments, only False Bay receives significant basin drainage, with 11 small catchments discharging to the bay. Near the coast, human activities include fishing, gathering medicinal plants and subsistence cropping. The loss of habitat and biodiversity as a consequence of mangrove use for fuelwood is regarded as a major issue.

Sub-region 5. Nile: trans-boundary river system, the damming of which has led to profound changes in fluxes through the Nile delta and in the associated Mediterranean Sea. These changes are exacerbated by a rapid growth of urbanisation and industrialisation around Cairo and changes in agricultural practice in the Nile River valley and its delta region. All of these socio-economic drivers, together with the natural driver of climate change, have produced significant impacts at the coast. Notable among these has been the acute coastal erosion around the mouths of the Rosetta and Damietta distributaries of the delta, largely attributed to the almost complete cessation since the 1960s of coarse sediment flux below the Aswan dam. Damming is also responsible for the increasing salinisation of groundwater in the delta area. Other important coastal issues include eutrophication and pollution of the coastal waters from the discharge of urban and industrial wastewater (Mex Bay and Abu Qir Bay) and the loss of habitat resulting from the land-filling of coastal lagoons.

Sub-region 6. East Africa (Somalia to northern Mozambique): medium basins, seasonally flushed by rainfall principally occurring during the transitions between the north-east and south-east monsoons in April and October. All basins discharge on a coast that is characterised by fringing or patch coral reefs with an associated rich biodiversity. The Rufiji discharges through a delta dominated by mangrove forest into coastal waters that include the largely pristine Mafia Marine Park. Both the Sabaki and Tana rivers intermittently discharge sand and fines, the sand being transferred to beaches thence in part to dune systems that characterise the coast of northern Kenya. Coastal erosion and the discharge of sediment are two important issues on this coast. Fine sediment carried in suspension as plumes through the coastal waters may settle and smother growing coral. The contributions that damming, deforestation and changes in agricultural practice make to sediment input have been the subject of several studies in the Tana and Sabaki. The Tana headwaters are already dammed and additional dams are proposed, as they are for the Rufiji. Pollution is recognised as being a significant issue in the Tana and Sabaki basins with agriculture, industry and urbanisation all contributing. In the Rufiji, pesticides used in rice cultivation and the impacts of prawn farming are matters of concern, as are the impacts of population growth and the clearing of mangroves for agriculture. Pollutants and nutrients (untreated or partially treated sewage) delivered to coastal creeks from the urban-industrial centres of Mombasa and Dar es Salaam may be significant.

Sub-region 7. Central/south Mozambique: medium (Incomati) and large (Zambezi, Limpopo) catchments with high seasonality in runoff and subject to extreme cyclonic events; an estuarine/deltaic coast characterised by beach plains and mangrove-fringed creeks. The assessed catchments (Zambezi, Limpopo and Incomati) are trans-boundary systems. The rivers discharge on a predominantly alluvial coast formed mainly of older beach deposits and barrier bars and spits with associated creek systems, mangrove swamps and sand dunes. Most of the coastal issues and impacts are ascribed to damming and agricultural drivers/pressures, with reduction in stream flow a significant to acute and increasing problem. The middle course of the Zambezi River has been interrupted by two major artificial impoundments – Lake

◀

Kariba and Lake Cahora Bassa – which cover 5364 km^2 and 2739 km^2, respectively. Coastal erosion reported for the Zambezi delta and the Incomati River is attributed solely to damming. Loss of biological productivity, particularly in the Zambezi system, is partly a consequence of water abstraction for irrigation. The increasing salinisation of agricultural land flanking the Incomati estuary and the nutrient depletion in the coastal seas off the mouths of the Zambezi and Incomati are regarded as impacts of damming.

Sub-region 8. South-east Africa: ranging from sub-tropical in the north to warm temperate on the Cape coast and characterized by medium (Thukela, Great Fish) and small (Groot Brak, Kromme) catchments. The catchments assessed in this region comprise one medium basin (the Thukela, discharging on to the sediment-based, biologically significant Thukela Bank on the east coast) and three small basins (the Great Fish, Kromme, Groot Brak). The coast adjoining all these systems is dominated by oceanic processes being open and subject to strong wave action and longshore drift. The Thukela is the largest east coast system and is a source of water (via inter-basin transfer) for industries in the Johannesburg area and irrigation along the Vaal River, a tributary of the Gariep. The Great Fish lies in relatively arid areas and its flow has been enhanced and stabilised by the inter-basin transfer of water from the Gariep. This has significantly changed salinity gradient patterns in the estuary. The Kromme is a small system which, despite a greatly reduced freshwater input because of dam construction, retains an open mouth because of the local coastal morphology. The reduced freshwater supply has resulted in a marine-dominated, clear-water system totally different from the original estuarine community. The Groot Brak is a small system significantly impounded but also extensively investigated and manipulated to protect housing developments in the lower reaches.

on the hydrological regimes within river basins cause changes that are being translated through drainage systems into the coastal zone, including the adjacent seas.

4.3.2.2 *Coastal Issues – State Changes and Impacts*

Coastal Geomorphology (Erosion, Siltation)

Changes to the geomorphology of the coast in the vicinity of river mouths are common in the region. The processes may be erosion, as around the deltas of many of the major rivers (e.g., Volta, Nile, Zambezi) or, more unusually, accretionary (e.g., the Malindi shore in Kenya, adjoining the Sabaki). While human activities in the catchments, notably damming, water diversion and abstraction, undoubtedly play a major role, other drivers including extreme climatic events, climatic variability (e.g., monsoonal), sea-level rise and coastal engineering may also contribute. The case of the Nile is perhaps the best documented, with a clear demonstration of the linkage between the commissioning of the Aswan Dam in 1968 and rapid shoreline retreat at the mouths of the main distributaries to the Mediterranean Sea.

Reductions in river flow and discharge due to damming have caused sedimentation in many lower reaches and estuaries (e.g., Senegal and Southwest Africa). In some cases (Morocco, Southeast Africa) a lack of significant discharge has led to temporary closure or partial closure of estuary mouths by beach accretion. Reductions in river flow are held to be responsible for the growing problem of aquatic weeds (e.g., in Senegal and Volta deltas). They may also be the cause of increasing groundwater salinisation leading to losses in agricultural productivity in several estuarine situations (e.g., Moulouya in Morocco, Senegal, Incomati in Mozambique), though this effect might be exacerbated by sea-level rise.

The commonly twinned drivers/pressures of deforestation and agriculture generally have a medium though increasing impact at the coast. These activities tend to increase both the severity of flooding and the amount of sediment carried as river bed load and in suspension. The problem is acute in the small to medium catchments of Morocco (Sebou and Moulouya) and East Africa (Tana, Sabaki and Rufiji). Settling plumes of suspended sediment discharged from the Sabaki have threatened the health of the coral reef in the Watamu Marine Park at Malindi in Kenya.

The increased mobilisation of sediment resulting from agriculture and deforestation has an important bearing on the sustainability of damming in many parts of the region. In Morocco, particularly, some reservoirs are rapidly becoming operationally ineffective due to siltation.

Pollution and Eutrophication

Eutrophication at the coast as a consequence of agriculture is generally a medium-ranking, though increasing, issue for many rivers including the Moroccan rivers, the Niger and Cross rivers in Nigeria and the East African rivers. The Nile is considered to be a hotspot although such pollution is decreasing.

Eutrophication and contamination at the coast from urbanisation (or other human settlement) and industry are middle-ranking, though increasing. Acute areas are the Volta in Ghana where there are related human health issues, and the Cross River where there are serious issues of oil-related pollution. Some of the most acute problems of coastal pollution and eutrophication are derived from urban-industrial nodes within the coastline area itself, including the coastal strip at Casablanca in Morocco, Saldanha Bay and Cape Town in South Africa, the Alexandria coastal strip in Egypt and the industrial centres of Mombasa and Dar es Salaam in East Africa.

Salinisation

In the North West and West Africa, increasing salinisation is a serious issue caused variously by urbanisation and

Table 4.4. Africa. Links between coastal issues/impacts and land-based drivers; overview and qualitative ranking at regional/sub-continental scale. (Category: *1*, low; *10*, high. Trend: ⇒ stable, ⇑ increasing, ⇓ decreasing; numerals for sub-regions refer to Text Box 4.5, Fig. 4.8a)

Coastal impact/ issues	Anthropogenic drivers	West Coast			Nile Delta		East Coast		
		Category	Trend expectation	Sub-regions particularly affected	Category	Trend expectation	Category	Trend expectation	Sub-regions particularly affected
Erosion	Damming/ diversion	8	⇑	(2) Senegal, Volta, Niger	8	⇑	5	⇑	(7) Zambezi
	Deforestation	7	⇑	Most sub-regions (small and medium size catchments)			6	⇑	Most sub-regions (small and medium size catchments)
Sedimentation	Damming/ diversion	6	⇑	Major in (1, 2)	(local)		4	⇑	(6) Malindi coast, Kenya – major
	Deforestation	(4–5)	⇑	Most sub-regions (small and medium size catchments)			4–5 (7 local)	⇑	Most sub-regions (small and medium size catchments) locally major
	Agriculture	3–4	⇑	(2) Cross, (4) Gariep, Olifants, Berg			6	⇑	(6) Tana, Sabaki, Rufiji
Eutrophication	Agriculture	6–7	⇑	Major or medium ranking for most sub-regions, in particular in small and medium size catchments in 1	5–?	?	3–5	⇑	Minor most sub-regions, medium in particular in small and medium size catchments in (6)
	Urbanisation	8	⇑	Mostly in (1, 2)	8–?	?	3–5	⇑	
Pollution	Agriculture	2–7	⇑	Minor for most sub-regions, in particular in small and medium size catchments in 1, major in 2	7	⇓	6	⇑	Medium ranking for most sub-regions, in particular in small and medium size catchments in (6)
	Urbanisation/ industrialisation (incl. mining locally)	6	⇑	Mostly more coastal (1, 2, 4)	7	⇒	4	⇑	Mostly more coastal (6)
Salinisation	Damming/ diversion/ multiple drivers	6	⇑	(1) Moulouya, (2) Niger delta			7–8 (local)	⇑	(6) Tana, (7) Incomati
Nutrient depletion	Damming						5–8	⇑	(7) Southern Mozambique, (8). KwaZulu-Natal
Biodiversity loss	Various drivers	7	⇑	Almost all sub-regions	8	⇑	5–8	⇑	Almost all sub-regions
Human health issues	Various drivers	7	⇑		8	⇒/⇓	5	⇒/⇑	

agriculture (by over-abstraction of groundwater) and the natural drivers of climate change and sea-level rise. Salinisation is seen as a problem in the Niger and Cross, where the drivers are unclear, and the Senegal, where climate change (drought) is regarded as the cause. In South West Africa, during prolonged low-flow periods, salinisation in the lower reaches, particularly of the groundwater resources, has become a concern.

Biodiversity and Harvestable Resources

Loss of biodiversity and reduction in habitat are issues for all sub-regions. Generally, the linkages to drivers or pressures appear to be complex, with a wide range of contributions from land-based and coastal human activities as well as climate change. However, nutrient depletion has been identified as one key pressure associated with reduced fresh-water discharge. Damming and water abstraction result in serious reduction or depletion of land-sourced nutrients and organic matter in estuarine and coastal waters. The impacts of such depletion result in the increasing loss of biodiversity in the waters off Mozambique (Zambezi delta, Sofala bank) and KwaZulu, Natal.

4.3.3 State Changes, Impacts and Future Trends

Among the usual human activities that affect catchments, damming is the most significant driver/pressure through marked reductions in the volumes of fresh water discharged and by disruption of natural flooding regimes.

The main points from the regional synthesis are:

- Coastal erosion and sedimentation are significant and progressive impacts in nearly all sub-regions, the problems being acute on the Nile Delta and West African lagoon systems. Damming is the principal driver, with reductions in river flow and sediment flushing;
- Damming (with reductions in river flow) contributes to estuarine salinisation (sea water intrusion into groundwater; e.g., the Incomati river in Mozambique), and to nutrient depletion in the coastal sea with the consequent loss of biodiversity (e.g., off KwaZulu, Natal);
- In most sub-regions deforestation and agriculture are important drivers, particularly with respect to coastal sedimentation from medium and small catchments (e.g., the Tana and Sabaki rivers in Kenya);
- In the large West African catchments, human settlement is a major contributor to eutrophication and the proliferation of aquatic weeds;
- Serious levels of eutrophication and pollution are mostly restricted to coastal urban-industrial sources (e.g., Alexandria, Mombasa, Saldanha Bay and Cape Town); and
- Loss of biodiversity or biological functioning is a common issue, related to a complex interplay of human and natural drivers.

In ranking the coastal issues and impacts, it has proved difficult to achieve a consistency in standards between, and even within, sub-regions. Even in simple cases, the ranking of the issues and impacts and the state changes has largely been a process of expert judgement within the limitations of the often sparse data. This applies to scientific data and particularly to socio-economic infor-

Table 4.5. Africa. Major activities, present status and trends affecting the coastal zone. (Trend: ⇒ stable, ⇑ increasing, ⇓ decreasing; *numerals* refer to sub-regions described in Text Box 4.5, Fig. 4.8a)

Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations	Sub-regions particularly affected
Damming and diversion	Erosion sedimentation	Major	⇑	Almost all sub-regions, with (2) and (5) as particular "hot spots"
	Salinisation	Local	?	(1, 7)
	Nutrient depletion			(7, 8)
Various drivers	Biodiversity loss	Major	⇑	Almost all sub-regions
Deforestation	Erosion sedimentation	Medium		Medium ranking for most sub-regions, however, major for coastal impact generated in small and medium size catchments in (1) and (6)
Agriculture	Eutrophication pollution			
Urbanisation				Medium overall but major in 5
Industrialisation	Pollution			As above, but in most cases more coastal than catchment-based (more pronounced in 4, 5, 6)

Table 4.6.
Africa. Priority driver/pressure features by country and corresponding "hot spots" (*numerals* refer to sub-regions described in Text Box 4.5, Fig. 4.8a)

Country	Driver/pressure	Hot spots
Morocco (1)	Damming	Sedimentation through reduced flushing especially on Mediterranean coasts; salinisation of coastal plains
	Human settlement, agriculture and industrialisation	Eutrophication, pollution on Mediterranean and Atlantic coasts
Senegal (2)	Damming	Sedimentation, invasion by aquatic weeds and loss of biodiversity in Senegal River; estuarine ecosystem destroyed
	Human settlement	Human health issues
Ghana (2)	Damming	Erosion of Volta delta and invasion by aquatic weeds
	Human settlement	Eutrophication and human health issues in Volta
Nigeria (2)	Industrialisation	Oil-related pollution in Cross and Niger
South Africa (4, 8)	Damming and diversion	Nutrient depletion off sourtheast coast with resulting biodiversity loss; sedimentation and loss of habitat on southwest coast
	Urbanisation and industrialisation	Eutrophication and pollution at Saldanha Bay
Egypt (5)	Damming and diversion	Erosion of Nile delta
	Urbanisation and industrialisation	High levels of pollution and eutrophication in Abu Qir Bay, Mex Bay and on Alexandria city coast
Kenya (6)	Damming	Deterioration in Tana water quality
	Deforestation	Siltation at mouth of Sabaki
Tanzania (6)	Deforestation	Siltation at mouth of Rufiji
	Agriculture	Deterioration of Rufiji water quality
	Aquaculture	Pollution from prawn fisheries
Mozambique (6, 7)	Damming and abstraction	Biodiversity loss in Zambezi delta and on Sofala Bank
		Salinisation of Incomati
		Erosion of Zambezi delta

mation. Time-series data generated from routine monitoring programmes are rare. Information regarding the coastal environmental state within the region varies greatly in both its quality and availability. The scarcity of data, apart from South Africa, is a serious impediment to the understanding of the driver-impact linkages throughout much of the continent. This may have influenced the assessment output. However, for Africa a preliminary ranking order of the principal land-based drivers and pressures was drawn up together with expected future trends in impacts (Table 4.5).

Taking account of these limitations, the identification of areas calling for increased future scientific and/or management attention still seems appropriate, at least to inform future agendas. One needs to be aware of the risk that local, possibly short-term acute issues may have attracted higher rankings, while more spatially widespread and longer-term impacts that have been assigned lower rankings may turn out to be the more significant. With this in mind, a first-order list of future areas of concern has been developed, some of which are now foci for a new START/LOICZ "AfriCat" pilot project (*http://www.loicz.org*).

4.3.4 Conclusions – Africa

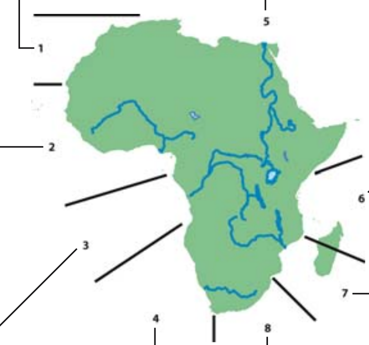
In general the AfriBasins data are typical of developing economy situations where economic growth and water use exceed the development of the necessary urban and industrial infrastructure. This finding parallels those for the South American and East Asian Basins assessments (Lacerda et al. 2002; Hong et al. 2002). However, heterogeneity of the sub-regions seems to be more pronounced in Africa than in other continents, making the ranking of issues and drivers in Africa a more complex challenge.

Within Africa, damming is the most significant driver/pressure resulting in marked reductions in the volumes of freshwater discharged and disruption of natural flooding regimes. During the last 50 years, damming, water diversion and water extraction have become common practices within the region, particularly in South Africa, principally for agricultural irrigation but also importantly for potable water supply and hydroelectric power generation. New dams and diversions are in their planning stages. In all the sub-regions, dam-related impacts at the coast were, with few exceptions, reported as show-

Sub-region 1 · North-West Africa – no info.: Algeria and Tunisia involved			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Salinisation	Major	?
	Nutrient depletion		?
	Erosion/ sedimentation		⇑
Various	Biodiversity loss	Major	⇑
Deforestation	Erosion/ sedimentation	Major	⇑
Agriculture	Eutrophication/ pollution	Major	⇑
Urbanisation	Eutrophication/ pollution	Medium	⇑
Industrialisation	Pollution	Medium	⇑

Sub-region 5 · the Nile			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Erosion/ sedimentation	Major "hot spot"	⇑
Various drivers	Biodiversity loss	Major	⇑
Urbanisation	Eutrophication/ pollution	Major	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Agriculture	Eutrophication/ pollution	Medium	⇑
Industrialisation	Pollution	Medium (locally major)	⇑

Sub-region 2 · West Africa			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Erosion/ sedimentation	Major (hot spot)	⇑
Various	Biodiversity loss	Major	⇑
Deforestation	Erosion/ sedimentation	Medium	⇑
Agriculture/ urbanisation	Eutrophication/ pollution	Medium	⇑
Industrialisation	Pollution	Medium	⇑



Sub-region 6 · East Africa - Somalia to northern Mozambique			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Erosion/ sedimentation	Major	⇑
Various drivers	Biodiversity loss	Major	⇑
Deforestation	Erosion/ sedimentation	Major (small catchm.)	⇑
Agriculture	Eutrophication/ pollution	Medium	⇑
Urbanisation	Eutrophication/ pollution	Medium	⇑
Industrialisation	Pollution	Medium (but local)	⇑

Sub-region 3 · Congo (note of caution: limited information on land based drivers and trends!)			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Deforestation	Biodiversity loss	Major	⇑
Urbanisation	Biodiversity loss	Minor	⇑
Industrialisation	Pollution	Minor	⇑

Sub-region 7 · Central East Africa / south Mozambique			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Erosion/ sedimentation	Major	⇑
	Salinisation;		?
	Nutrient depletion		?
Various drivers	Biodiversity loss	Major	⇑
Agriculture/ urbanisation	Eutrophication/ pollution	Medium (locally major)	⇒

Sub-region 4 · South-West Africa			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Erosion/ sedimentation	Medium	⇑
Agriculture	Eutrophication/ pollution Biodiversity loss	Medium	⇑
Urbanisation	Eutrophication/ pollution	Medium (but local)	⇒

Sub-region 8 · South-East Africa			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Agriculture	Eutrophication/ pollution	Medium	⇑
Various drivers	Biodiversity loss		⇑
Industrialisation	Pollution	Medium	⇒
			⇑ (locally)
Damming/ diversion	Erosion/ sedimentation; Salinisation; Nutrient Depletion	Minor (locally medium)	⇑
Urbanisation	Eutrophication	Minor (locally medium)	⇒

Fig. 4.9. Africa. Sub-regional synthesis and typology of river catchment–coast interactions

ing increasing trends. This is supported by case studies and "hot spots" shown in Table 4.6.

Agriculture and deforestation are contributing to significant increases in soil erosion and consequently increased sediment flux and discharge. Agriculture, together with urbanisation and industrialisation, is contributing to the increasing degradation of water quality discharged to estuaries and coastal seas leading to growing problems of pollution and eutrophication and related human health issues.

All the socio-economic drivers referred to above play a part in the reported loss of biodiversity throughout the region, principally through the destruction of habitat and reduction in the volume and quality of freshwater discharged through the coastal zone to the coastal seas. Figure 4.9 is a sub-regional synthesis of main river catchment-coastal change issues, and provides an expert judgement-based ranking and trend analysis.

4.4 East Asia

4.4.1 Overview of East Asian River Catchment-Coastal Zone Systems – Geography and Climate

The East Asian region, comprising the eastern and southern side of the Euro-Asian continent, encompasses a wide range of climatic zones extending from tropics to Arctic tundra. A characteristic of this region is the East Asian Monsoon, with wet summers and dry winters; rainfall is generally higher in the south and lower in the north. East Asia is dominated by a number of large river catchments and wetlands to the east and south of the Himalayas, as well as eastward-flowing rivers traversing grasslands in the cold temperate far east of the Russian Federation. These rivers influence extended areas of the coastal zone in the southern and central region, but large parts of the coastline are also influenced by relatively small and medium-sized catchments. Riverine fresh water and nutrient supply dominate the biogeochemistry of the shelf regions in the marginal seas, determining most of the primary production and fisheries of the East Asian marginal seas – having a major role in the South China Sea, East China Sea, Yellow Sea, Bohai Sea and Sea of Japan and a lesser role in the Sea of Okhotsk and the Bering Sea.

While most coasts of East Asia are tectonically passive, the coasts of Taiwan and Japan are active and have small drainage basins that exhibit relatively high rates of water and sediment discharges. Smaller drainage basins have less area to store sediments so that their sediment yield increases by as much as 7-fold for each order of magnitude decrease in basin area.

A sub-regional classification, based on expert judgement, has delineated natural climatic and catchment characteristics and accounted for differences in the an-

Fig. 4.10. East Asia. The sub-regions identified in the East Asia Basins study and a selection of river catchment-coast systems evaluated (from Hong et al. 2002)

thropogenic use pattern (Fig. 4.10, Text Box 4.6; Hong et al. 2002). There is extensive and intensive agriculture and aquaculture associated with a large population in the southern tropics, agriculture and industrial development linked to a large population in the temperate region, and terrestrial mining and offshore oil and gas exploitation allied to a sparse population in the cold temperate and Arctic regions.

Text Box 4.6. East Asia: catchment sub-regions

From Hong et al. (2002)

Sub-region 1. South China Sea: comprises the coast of Vietnam and South China from 7° N to the Tropic of Cancer, corresponding to the high rainfall region. On the Vietnamese coast, two large rivers (Mekong and Red), plus 114 smaller rivers discharge into the South China Sea while the Pearl River, China's third biggest system, marks the north-eastern boundary of the sub-region. The Mekong River (4880 km long, 0.795×10^6 km^2 catchment area) descends from the Tibetan plateau in China, crosses Myanmar, Laos, Thailand and Cambodia to Vietnam and deposits 1–3 cm of fertile silt each year on the lowland flood plains in Vietnam and Cambodia, sustaining these intensively farmed areas. In addition, river flow during the dry season is important for controlling salinity penetration into interior areas from the coast. The regional climate is humid tropical and dominated by monsoons. The Pearl River delta is in the subtropics and 80% of the annual discharge is in the wet season (April to September). Typhoons coincide with the wet season and flooding is common. The major drivers for the catchment changes are deforestation in the upper reaches of rivers, destruction of mangrove swamps, dike and dam building, channel dredging, agriculture, aquaculture, concentration of economic development and high population density. These drivers modify supply and distribution of water, sediments and nutrients.

In Vietnam some 42% of the total population of 77 million are resident in coastal areas Water is in great demand for rice production. Agriculture depends heavily upon chemical fertilisers and pesticides. Pesticide residues are transported by rivers to the coastal zone where they accumulate in the bottom sediments and aquatic organisms. Forest in the upper reaches of the Mekong River has been reduced from 43% in 1943 to 28% in 1995.

Further driver/pressure are urban waste, agriculture, aquaculture and transportation resulting in severe eutrophication. Man-made grow-out ponds that have replaced wetlands are highly enriched with fertilisers and serve as sources of dissolved and particulate nutrients. Demand for transportation and related traffic infrastructure lead to increased inputs of oil and other contaminants. In general, major drivers in the catchment and delta of the Pearl River are population growth, industrialisation and urbanisation leading to excess nutrient loads, organic contaminants and oil.

Sub-region 2. East China, Yellow and Bohai Seas, Taiwan Island: stretches from the Tropic of Cancer to 41° N and includes temperate coasts and the mouths of the Changjiang (Yangtze), Huanghe (Yellow), Hai and Liao rivers, with numerous medium and small rivers along the coasts of China and the Korean Peninsula. The Chinese continent dominates river discharge, is influenced by the East Asian monsoons but covers a wide climatic range from arid-temperate to humid tropics. The Changjiang (Yangtze) is the fourth largest river in the world in terms of water flow and sediment load. Construction of the Three Gorges dam will reduce the sediment discharged to the coast. The atmospheric pathway is a significant conduit of terrestrial materials to the ocean due to persistent westerly winds and the arid Gobi Desert areas and Loess Plateau region. The Korean rivers are steep, relatively short, with small drainage areas and relatively high sediment yields. Monsoonal Taiwan experiences typhoons and thunderstorms during the wet season which brings 80% of its annual precipitation.

While cultivated land area has decreased in China, the irrigated area has increased. Consequently, damming is a continuing activity affecting numerous Chinese river systems. Trapping efficiency is near 100% in some catchments, such as the Yellow (Huanghe). The application of chemical fertilisers caused the DIN concentration of the Changjiang and Huanghe to double in last two to three decades. Most industrial wastewater is pre-treated before discharge. Three large reservoirs in the Changjiang were built between 1968 and 2003 (including the Three Gorges dam) and the diversion of 1000 m^3 s^{-1} of water from the lower Changjiang to North China has been under consideration. The construction of the dams has reduced sediment transport downstream while deforestation in Sichuan has resulted in very high sediment loads due to serious soil erosion. The Yalujiang is dammed and the lower reaches receive a considerable amount of wastes from both non-point (e.g., agriculture) and point (e.g., domestic and industrial activities) sources.

The population density in Korea (471 persons km^{-2}) ranks as one of the highest in the world. Urbanisation, industrialisation and aquaculture has been rapid. Water resources in South Korea are fairly limited so there are large storage reservoirs around the country. Overuse of fertilisers, pesticides and insecticides in agriculture has led to pollution of rivers and streams.

Pressure from people on coastal zones of Taiwan is aggravated by the fact that most people live on the limited coastal plains. Pressure to move people inland has led to road construction and deforestation, both of which have contributed to an already high denudation rate of top soil. As a consequence of this, thirteen rivers in Taiwan are now ranked among the top 20 worldwide in terms of sediment yield. Together with agricultural fertiliser use this anthropogenic forcing may account for some 50% of the total particulate organic carbon and nitrogen fluxes from the Taiwanese islands.

Sub-region 3. The Sea of Japan, Sea of Okhotsk and Bering Sea: has a cold and relatively arid climate (33° N to the Arctic Circle, 66.33° N) containing the mouths of the Amur and Anadir rivers with medium and smaller rivers along the coasts of Siberia, Korea and Japan. The Tumen River (Tumenjiang) is frozen for 100–120 days yr^{-1} and experiences two flood periods; in April from the spring thaw and in July-August due to monsoonal rain. Peter the Great Bay has two inlets, Amursky and Ussurisky bays, with different types of drainage basin. The Amur is the world's ninth largest river, and its catchment contains significant agricultural areas as well as supporting biota of the taiga and subtropical forests. The basins in the Bering Sea are relatively pristine; the Anadyr River basin in north-eastern Siberia is an almost pristine watershed, lacking major industrial or agricultural activity, but mining activities pollute with heavy metals. The few river catchments emptying into the Sea of Japan, Sea of Okhotsk and Bering Sea are very different from the other regions in terms of human impacts since the region is scarcely populated, with human impact on the coastal zone localized to the few coastal cities. During the past decade, agricultural production in the Amur region has increased 3- to 4-fold and poor farming practices, such as burning straw and extensive use of herbicides and pesticides, have damaged soils, wildlife, human health and the economy. In the Tumen catchment, basically the only regional area of concern, industry within the watershed includes engineering, chemicals, materials processing, papermaking, rubber, textiles and printing, and further industrial development is planned.

4.4.2 Assessment of Land-based Drivers, Pressures and Coastal Impacts

Although anthropogenic pressures vary across East Asia, most rivers have been markedly altered by human activities or are subject to management plans affecting land and water use. The resultant drivers/pressures on the coastal zone are more pronounced than in other areas of the world. China alone supports more than 1 billion people, accounting for one-sixth of the world population. Consequently, changes in land use, pollution and water diversions have altered the horizontal mass transport of materials, and are likely to cause comparatively large coastal state-changes and generate zones of impact throughout the marginal seas of East Asia. The islands of Japan and Taiwan are also heavily populated, and human interference in the river catchments and flow regimes is extensive. There are pronounced differences among the sub-regions, particularly between the northern and southern groups highlighted in the sub-regional synthesis (Fig. 4.11).

4.4.2.1 *Drivers and Pressures*

The patterns of climate, including monsoons, and population distribution underpin the differences between the type and intensity of drivers and pressures across the three sub-regions of East Asia. In the southern sub-region, water extraction, diversion and damming usually in association with agriculture and locally intense urbanisation are principal drivers for coastal change. Increasing aquaculture ventures and industrial developments, coastal urbanisation and a high density coastal population add further pressures. Damming, mainly for hydroelectric power, and increasing urbanisation within an already high population density are the major drivers and pressures in the central region of East Asia. Deforestation in upper catchments is a continuing concern. By comparison, while the coastal zone of the sparsely populated northern sub-region sustains localised pressures from coastal urban areas, industrial development (including oil exploration) represents the major drivers and pressure elements (Table 4.7).

4.4.2.2 *Coastal Issues – State Changes and Impacts*

Sub-region 1: Vietnam and South China Sea

Coastal Geomorphology and Salinisation

In Vietnam, despite the building of dykes for coastal protection over the last millennium, the intensity and frequency of coastal flooding has increased in recent decades due to the combined effect of upstream deforestation, sea-level rise and blocking of waterways by the increased sedimentation at lagoon inlets and river mouths. Coastal erosion and accretion are rapid in the Mekong River delta (MRD) and Red River delta (RRD) posing major threats to the coastal development. The mean rate of coastal erosion increased along the Vanly coast after completion of large Hoa Binh Dam in the Red River catchment in 1989; a larger Son La dam is planned for the upper Hoa Binh River. By contrast, in the MRD coastal accretion has occurred on the Camau Peninsula. Also the RRD has expanded seaward 27 $m\,yr^{-1}$ with a maximum rate of 120 $m\,yr^{-1}$, and 360 $ha\,yr^{-1}$ have been added to the delta. Landward saltwater intrusion occurs as far as 50 km into the Red River and 70 km into the Mekong River due to decreased river flow in the dry season exacerbated by water abstraction for irrigation. Decreased river water discharge due to dams and irrigation in the upper reaches of the rivers and to sea-level rise will lead to enhanced saltwater intrusion.

Eutrophication

Eutrophication is widespread in southern Vietnam due to wastewater input from domestic activities, agriculture and aquaculture. The most significant impact derived from the rapid economic growth in the Red River basin is increased nitrogen loading to the coast. Pronounced state changes in the receiving marine environments of the Pearl River result from eutrophication yielding algal blooms, oxygen depletion and contamination of water resources. Red tides occur frequently in the western part of Hong Kong. The dinoflagellate bloom of *Gymnodinium mikimotoi* in 1998 resulted in massive fish kills and the loss of fish stocks.

Pollution

Oil is the most prominent contaminant in Vietnamese coastal waters, while pollution from the heavy metals occurs in some localised areas. Coastal mining for coal, sand, gravel and heavy minerals changes the morphology of the coastal landscape and subsequent dumping of solid and liquid waste degrades coastal water quality. Persistent organic pollutants (POPs) and chloro-pesticides have contaminated both the river water and sediment of the Pearl River delta. The urban wastewater discharges from the eight major cities of the region have reached almost 70% of the total Guangdong's Province discharges (Guangdong Province Environmental Protection Bureau 1996; Wong and Wong 2004). Chen (1994) estimates an annual regional generation of up to 2 billion and 560 million t industrial and domestic waste, respectively.

Table 4.7. East Asia. Links between coastal issues/impacts and land-based drivers; overview and qualitative ranking at regional/sub-continental scale. (Category: *1*, low; *10*, high. Trend: ⇒ stable, ⇑ increasing, ⇓ decreasing; numbers for sub-regions refer to Text Box 4.6, Figure 4.10)

Coastal impact/ issues	Anthropogenic drivers	Vietnam and South China (1)			Central China, Korea, Taiwan, Japan (2)			North East Asia (3)	
		Category	Trend expectation	Sub-regions particularly affected	Category	Trend expectation	Sub-regions particularly affected	Category	Trend expectation
Eutrophication/ red tides	Agriculture/ aquaculture	1–9	⇑	Locally	7–9	⇒	(Including Korea)	2	⇑
	Urbanisation/ industrialisation	1–9	⇑	(Major in Mekong, Red and Pearl River/Delta)	9–10	⇑	(Including Japan)		
Erosion/ sedimentation	Damming/diversion	2–10	⇒/⇑		10	⇑			
	Agriculture	2	⇒		8	⇒		2	⇒
	Deforestation	1–9	⇓		8	⇒		2	⇑
	Land reclamation	2–9	⇒						
	Sediment mining	1–9	⇒						
Coastal flooding	Deforestation	2–9	⇓					2–3	⇑
	Land reclamation	2–8	⇒/⇑		2–8	⇒/⇑			
Land subsidence	Groundwater pumping/erosion				4–10	⇒/⇑	(Central China and Taiwan)		
Salinisation	Agriculture/damming	1–8	⇒	Locally					
	Deforestation	2–5	⇓						
	Sediment mining	1–9	⇒	Locally					
Pollution	Mining and oil (on and off shore)	3–6	⇒					1–4	⇒
Biodiversity loss (modification)	Various drivers	4–10	⇒/⇑		3–5	⇑	(Central China and Taiwan)		

Table 4.8. East Asia. Major activities, present status and trends affecting the coastal zone. (Trend: ⇒ stable, ⇑ increasing, ⇓ decreasing; *numerals* refer to sub-regions described in Text Box 4.6, Fig. 4.10)

Anthropogenic drivers	Major state changes and impacts	Present pressure status	Trend expectations	Sub-regions particularly affected
Urbanisation/ industrialisation	Eutrophication/pollution/Harmful Algal Blooms (HABs) Water extraction	Major/medium	⇑	1, 2 incl. Japan, Taiwan, (locally 3)
Damming/diversion	Freshwater, nutrient, and sediment sequestration/coastal erosion	Major/medium	⇑	1 (locally), 2 incl. Japan, Taiwan
Agriculture/ aquaculture	Eutrophication, pesticide pollution/ diseases	Medium/major	⇒/⇑	1, 2
Deforestation	Habitat loss/modification Erosion/sedimentation Saltwater intrusion	Medium/major	⇒/⇓	1, 2,
Land reclamation	Sediment budget alteration	Medium (locally major)	⇑	1, 2
Mining (terrestrial and offshore)	Biodiversity loss	Medium/minor	⇒	1, 3

Biodiversity and Harvestable Resources

Recent natural and human-induced coastal land changes have led to the loss of tidal flats, mangroves, beaches, seagrass beds and coral reefs with > 30% of the mangrove forests converted to shrimp aquaculture ponds in the delta regions, significantly changing the coastline. Mangrove forest has been reduced from 400 000 ha in 1943 to 170 000 ha in 1993, and > 24 000 ha of the tidal flood plain including salt marshes was reclaimed for agriculture between 1958 and 1995; coastal land has accreted seaward. Beaches have been reduced by erosion and sand mining, coral reefs and seagrass beds have been destroyed by increased turbidity due to flood-originated silt and freshening of water and increased pollution has degraded living resources for coastal and offshore fisheries.

Sub-region 2: East China Sea, Yellow Sea and Bohai Sea; Taiwan and Japan

Coastal Geomorphology

The rate of sediment supply from the Huanghe (Yellow River) into the Yellow and Bohai seas has changed significantly due to human intervention throughout Chinese civilization. The Huanghe no longer flows into the sea for a large portion of the year due to increased water consumption by industry, agriculture and a growing population during the last 20 to 30 years. Consequently, the regime shift in the Huanghe delta from rapid accretion to coastal erosion is a dramatic change in the development of the regional coastal geomorphology. Increased water demand in East Asian continues to accelerate construction of dams along most of the river courses leading to decreased sediment discharge to the sea. More than 90% of the Huanghe sediment load is deposited in the lower reaches of the river and within the estuarine area. After construction of the Danjiangkou reservoir in the Changjiang (Yangtze) catchment in 1968, the annual suspended sediment discharge was reduced by 99%.

Sediment trapping and nutrient depletion are seen to originate from intense Taiwanese damming and have contributed to the erosion of many coastal deltas and beaches, and loss of fisheries resources (Chen et al. 2004). Such impacts are exacerbated by over-pumping of groundwater; 1 000 km^2 of the flat lands have subsided in Taiwan.

Eutrophication and Pollution

The amount of Chinese national waste drainage entering the seas exceeded 6.5×10^6 t yr^{-1} in the 1990s, of which 80–90% was carried by rivers. The ratios among nitrogen, phosphorus and silicon in the coastal ocean has changed due to human impacts in the watershed, affecting phytoplankton. The previous "nitrogen limitation" has switched to a phosphate and silica-limiting environment and the major phytoplankton species have shifted from diatoms to flagellates with harmful algal blooms (HABs) occurring more frequently in recent decades.

Biodiversity and Harvestable Resources

In combination with overfishing and pollution, reduction in nutrient supply from rivers and upwelling will further aggravate the problem of marine resource sustainability. A correlation can already be shown between the anomalies of the Changjiang outflow and the fisheries catch per unit effort (CPUE) in the East China Sea. Syvitski (2003) quotes an 85% reduction of shrimp fishery in the Bohai Sea when sediment discharge of the Huanghe was reduced along with water and nutrient discharge.

Sub-region 3: Sea of Japan, Okhotsk Sea and Bering Sea

Coastal Geomorphology

Annual precipitation has increased in recent decades along the southern coast of Korea and Cheju Island leading to increased erosion and an increase in the material export from the land to the sea.

Pollution

Minor contamination of heavy metals, petroleum hydrocarbons and chlorinated hydrocarbons was noted in the coastal waters north of the Tumen River. However coastal issues originate mainly from waste water discharge from large cities (e.g., Vladivostok and Ussurijisk) and from heavy industries concentrated along the banks of Amursky Bay. Mining activities are contaminating the Anadyr and Rudnaya rivers and impacting coastal waters of the Bering Sea and the middle of Sikote-Aline coast.

4.4.3 State Changes, Impacts and Future Trends

The extreme climatic conditions of the East Asian monsoon and a variety of anthropogenic drivers generate growing impacts on the coastal zones and the water continuum (Table 4.8). Damming of rivers has significantly distorted the erosion-accretion equilibrium of large stretches of the East Asian coastline. These effects are most apparent where water resources are both abundant seasonally (i.e., Vietnam and South China) and where water resources are scarce due to population growth in the catchment areas, in coastal metropolitan areas or in arid climates. Examples can be found along the Vietnamese coast and in the old Huanghe delta and current Huanghe delta. Diversion of water resources in the upper reaches of the rivers and especially in the Great Western Development area in China which influences upper and middle reaches of the Yangtze and Yellow rivers.

Numerous examples reveal that the oceanic environment is changing due to either natural or human-caused variations in climate and river runoff (Chen 2000) affecting water quality and changes in the flood storage and drainage capacities of landscapes. Rivers in Vietnam and South China are experiencing serious harmful algal blooms that result in fish kills; in particular the expanding aquaculture sector is affected. Red tides are frequent in the Bohai Sea off the Liao and Hai rivers (Yu et al. 1999) and coastal areas of Taiwan, the Korean Peninsula and Japan, probably due to an increased influx of nutrients and changing nutrient ratios (e.g., silicate becomes an issue when the N and P increase to a point that the ratios of Si : P and Si : N are altered). Many of the excess nutrients are coming from atmospheric deposition, not just human activities that result in changes in river runoff quality.

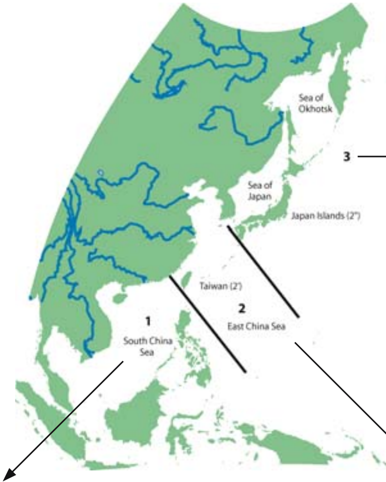
The most common contaminants in the coastal zone of East Asia are oil, polycyclic aromatic hydrocarbons (PAHs) and pesticides in Vietnam and South China (Sub-region 1), and heavy metals in the central area (Sub-region 2) and the northern area (Sub-region 3). Persistent organic pollutants (POPs) and heavy metals have been reported. DDT and HCH concentrations in oysters in the western waters of Hong Kong and in human breast milk were 2–10 times higher than those found in European and Canadian samples (Wong and Wong 2004, Wong et al. 2002). Oil pollution from offshore oil production has resulted in habitat loss in the coastal waters off Sakhalin Island. Most pollutant inputs are from agriculture and industrialisation along river catchments in Vietnam and South China (Sub-region 1) and the central sub-region (2), and from terrestrial and offshore mining (including oil exploration) in the northern sub-region (3). Atmospheric deposition is a major pathway for pollutants in northern East Asia.

Exploitation of living resources has resulted in habitat loss of mangroves, coral reefs and seagrass beds and led to decreases in the number of species and wetlands in Vietnam and South China. Fishery resources may decline with further contamination, overfishing or reduction of freshwater outflow of the Vietnamese and Taiwanese rivers, as well as the Yangtze River due to its damming and diversion. Overfishing and overcrowding of prawn cultivation affects about 1 000 km^2 offshore of the Hai and Liao rivers in the Bohai Sea. Coastal fisheries yields in the west of Taiwan have already been cut by half due to contamination and overfishing, an effect that exacerbates those pressures on the marine resources deriving from changing riverine material fluxes to the coastal waters.

In Vietnam and South China deltas (e.g., the Mekong, Red and Pearl rivers), saltwater intrusion affects rice agriculture and drinking water as well as spawning of prawns and fishes. In the central sub-region of China, inundation of deltaic lowlands by storm surges and high tides, and possible future sea-level rise, are concerns. Land subsidence in Shanghai and western Taiwan results from ground water extraction. In the Japanese islands, most sandy beaches are expected to be lost within the next 100 years due to sea-level rise.

4.4.4 Conclusions – East Asia

East Asia characterises the situation of developing economies and high population pressures, at least in the southern and central sub-regions, where economic growth frequently outpaces the necessary urban and industrial infrastructure. Hence, eutrophication, on the other hand



Sub-region 3 · North East Asia: Korean East Coast, Okhotsk and Bering Sea (note of caution: limited information on land based drivers and trends!)			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Urbanisation/ industrialisation	Eutrophication/ pollution	Minor (locally medium)	⇑ (locally)
Mining	Pollution	Minor (locally medium)	⇒
Deforestation	Erosion/ sedimentation/ flooding	Minor	⇑
Agriculture	Eutrophication/ pollution	Minor	⇑ ⇒

Sub-region 1 · Vietnam and South China: South China Sea			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Aquaculture	Pollution/ diseases	Major	⇑
Urbanisation	Eutrophication/ siltation/ water shortage	Medium (Major locally)	⇑
Industrialisation	Pollution/ salinisation	Medium (Major locally)	⇑
Damming/ diversion	Erosion/ sedimentation; Nutrient depletion	Medium, (Major locally)	⇒ ⇑
Agriculture	Eutrophication/ pollution	Medium, (Major locally)	⇒ ⇑
Land reclamation	Erosion/ sedimentation/ flooding	Medium (Major locally)	⇒ ⇑
Various drivers	Biodiversity loss	Medium (Major locally)	⇒ ⇑
Mining/ oil extraction	Pollution	Medium	⇒
Deforestation	Erosion/ sedimentation	Medium (Minor locally)	⇓

Sub-region 2 · Central China: East China Sea/ Yellow Sea; Japan and Taiwan			
Driver	**Major coastal impact**	**Present pressure status**	**Trend expectation**
Damming/ diversion	Erosion/ sedimentation; Nutrient Depletion	Major	⇑
Urbanisation	Eutrophication/ pollution	Major	⇑
Industrialisation	Pollution	Major	⇑
Agriculture	Eutrophication/ pollution (incl. red tides)	Major	⇒
Aquaculture	Pollution/ diseases	Major	⇒
Deforestation	Erosion/ sedimentation	Major	⇒
Groundwater pumping	Land subsidence	Medium (locally major)	⇒ ⇑
Land reclamation	Erosion/ sedimentation/ flooding	Medium	⇒
Various drivers	Biodiversity loss	Medium	⇑

Fig. 4.11. East Asia. Sub-regional synthesis and typology of river catchment–coast interactions

nutrient depletion and pollution in the coastal zone are major consequences from catchment-based activities, linked to urbanisation and the rapidly increasing demand for water and energy. Increased efforts in damming and diversion of river courses are allied with erosion/sedimentation problems at the coast. Agriculture and deforestation affect some areas, in particular those in southern East Asia where tropical typhoons bring torrential rain and cause pulsed freshwater discharges to the coast. All the activities listed in Table 4.8 result in a variable degree of change in the trophic state and food webs of coastal ecosystems and loss of living resources.

The flood cycle, linked to the monsoon rains, is a critical factor in the life cycle of many of the region's aquatic species; even slight changes in peak river discharge could threaten fish production and food security. Impacts observed near dams constructed on the Mekong River tributaries illustrate that altering the annual flood cycle, reducing the silt load of the water or diverting the river flow can have serious impacts on agriculture in the Mekong delta. Figure 4.11 is a sub-regional synthesis of main river catchment-coastal change issues, and provides an expert judgement-based ranking and trend analysis.

4.5 Russian Arctic

4.5.1 Overview of Russian Arctic River Catchment-Coastal Zone Systems – Geography and Climate

The length of the Russian coastline exceeds 60 000 km accommodating a population of 17×10^6 people. More than 40 000 km are Arctic coast, 27 000 km of which belong to the continental shoreline. Nine large rivers – Northern (Russian: Svernaya) Dvina, Pechora, Ob and its tributaries, Yenisey, Lena, Khatanga, Jana, Indigirka and Kolyma – flow to the Arctic Ocean from large catchment basins (Fig. 4.12). In fact all northern rivers on their way to the Arctic deltas pass through several climatic zones each associated with different human activities.

Northern, western and eastern areas of the Russian coastal zone have industrial development (mining, refining, shipbuilding, construction including defence industries) and commercial fisheries. All types of settlements, from well-developed urban areas on the Baltic Sea to small rural settlements on the northern seas, are represented but there is much more limited use of the coastal

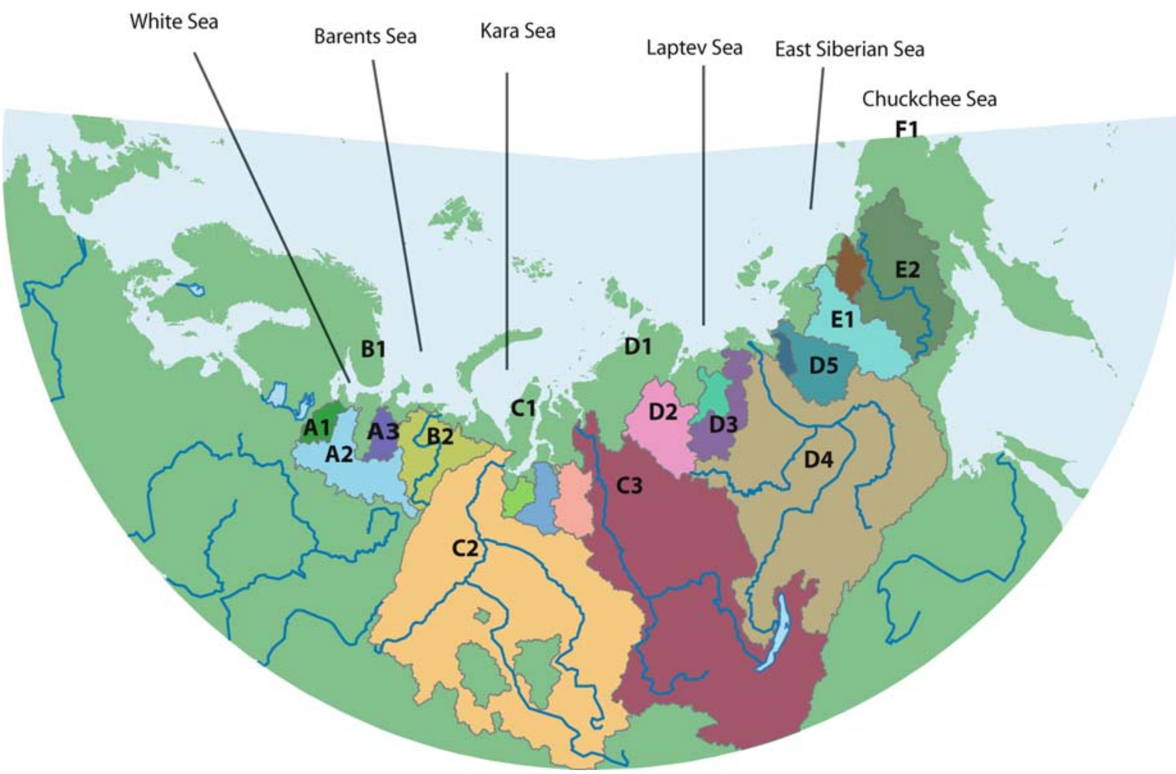


Fig. 4.12. Russian Arctic. The sub-regions identified in the Russian Arctic Basins study and a selection of river catchment-coast systems evaluated (from Gordeev et al. 2005): *Sub-region A*: White Sea: *A1* Onega River catchment basin, *A2* Northern Dvina (Ru: Severnaya Dvina) River catchment basin, *A3* Mezen and Kuloy River catchment basin. *Sub-region B*: Barents Sea: *B1* Kolsky Peninsula coast, *B2* Pechora River catchment basin. *Sub-region C*: Kara Sea: *C1* Yamal Peninsula coast, *C2* Ob River catchment basin, *C3* Yenisey River catchment basin. *Sub-region D*: Laptev Sea: *D1* Taymyr Peninsula coast, *D2* Khatanga River catchment basin, *D3* Olenek River catchment basin, *D4* Lena River catchment basin, *D5* Yana River catchment basin. *Sub-region E*: East Siberian Sea: *E1* Indigirka River catchment basin, *E2* Kolyma River catchment basin. *Sub-region F*: Chuckchee Sea: *F1* Chuckchee Sea coast

Text Box 4.7. Russian Arctic: catchment sub-regions

From Gordeev et al. (2005)

Sub-region A. White Sea: the Arkhangelsk region (A2 in Fig. 4.12), including the basin and mouth of the Northern (Severnaya) Dvina River and the coastal part of the White Sea. Ecologically, the White Sea is subdivided into two large parts:

- the eastern part with clean tidal waters but strong erosional impact with rates reaching 13–17 m yr^{-1} on the Tersky coast (eastern Kola Peninsula, B1 in Fig. 4.12) and the Kaninsky coast (north of A3 in Fig. 4.12);
- the western part (north west of A1 in Fig. 4.12), which has more internal bays and favourable conditions for accumulation of pollutants.

The surface water quality in the catchment of the Severnaya Dvina River is affected by timber processing, while the Arkhangelsk division contributes non-treated communal and industrial sewage into natural waters. Industrial development and commercial fisheries are impacting the traditional subsistence uses of biological resources carried out by the indigenous communities.

Sub-region B. Barents Sea: the far north-western part of the Russian coastal zone, the Murmansk region (B1 in Fig. 4.12) with 1730 km of diversified coastline including numerous fjords and bays. The large Kola Fjord is the most industrially-developed and populated part of the Russian north, receiving waters from the Kola River and other rivers of the Kola Peninsula, including: Patso-Yoki, Zapadnaya Litsa, Tuloma, Vorjema and Pechenga which together account for only 10% of the total sediment load to the Barents Sea. About 60% of the region's population is concentrated in the coastal zone. Biologically, the Barents Sea is the richest system of the Arctic Ocean due to advection of the warm Gulf Stream meeting with cold Arctic waters.

The south-eastern part of the Barents Sea is supplied by the Pechora River, the largest river of the lowland north-eastern part of Russia (B2 in Fig. 4.12). It supplies 70% of all river runoff into this coastal sea. The tundra zone in the catchment has relict islands of boreal forests. Some rivers are strongly impacted by mining, chemical, metallurgical and timber industries (e.g., Kola Peninsula and Murmansk regions), while other rivers experience little anthropogenic impact. In the Nenets Autonomous okrug or Pechora division (B2 in Fig. 4.12), industries, domestic and agricultural uses of floodplains are the main driving forces in changing the natural environment. Exploitation of oil and gas fields for chemical processing produces impacts though chronic environmental pollution and regular release of non-treated communal wastes and domestic sewage exacerbate the situation. A significant number of coastal and marine oil-fields will soon be accessed for further exploration and development.

Sub-region C. Kara Sea: Western Siberia (Tymen region, Khanty-Mansi and Yamal-Nenets Autonomous okrugs) with Russia's largest rivers: Ob, Pur, Taz, and Pjasina (C1, C2 in Fig. 4.12). They form a complex delta-estuarine areas and contribute 41% of the total runoff to the Arctic Ocean; the Ob River provides 37% of the runoff to the Kara Sea. Widespread bogs and marshes increase massively from north to south reflecting the growing thickness of the underlying permafrost in high latitudes. The catchment basin of the Ob River gathers water from the territories of seven administrative regions of Russia, which form the Western Siberia macro-region with a population 16.74 million people and is subject to industrial pressures and natural resource exploitation.

The Kara Sea subdivision (C3 in Fig. 4.12) in Eastern Siberia (Krasnoyarsky Kray, Evenkysky, Taymyr (Dolgano-Nenets) autonomous okrugs) has the largest river of Russia, the Yenisey River and its 190 000 tributaries which drain an area of 2.58×10^6 km^2 along a length of 3500 km. Tributaries are concentrated in mountains to the east of the catchment. The river mouth is a dynamic estuarine delta with numerous channels; Yeniseyskaya Guba and the semi-enclosed Yenisey Bay cover some 20 000 km^2. The Ob River basin is highly industrialized, with oil and gas activities dominating. The central and southern regions of Western Siberia contain a diversity of industry, including materials processing, coal-mining, agriculture, transport, building materials manufacture, pipeline construction and military enterprises. Dams on the Ob River have had no significant impact on the volume of river flow, but coal-mining wastes and agricultural pollution have led to significant ecological impacts. Middle and northern reaches of the Ob River and its tributaries have pollution from crude oil and its products. The most prominent anthropogenic drivers in the Yenisey catchment are industry (mining, non-ferrous metallurgy, chemical plants, timber, pulp and paper production) agriculture, navigation, housing and communal holdings and the environmental state of the whole river is assessed as critical.

Sub-region D. Laptev Sea: receives runoff from four large rivers: Khatanga, Lena, the Olenek and Jana (D in Fig. 4.12). The 4400 km-long Lena River has one of the largest catchment basins in Russia (2.49×10^6 km^2). Its delta is large, with a complex dynamic where strong flows of river sediments have formed some 6089 channels, 58728 lakes and 1600 islands in a total area of 32 000 km^2. Permafrost is widespread and the coastal zone contains a narrow strip of tundra further south followed by forest-tundra and taiga forests.

Sub-region E. The East Siberian Sea: a shallow sea, where tidal activity is significant because of the very narrow strip of water free of ice. Annually the shoreline recedes at a rate of 4–30 m and some 10–50 km have been lost since the shoreline stabilised some 5–6 000 years ago. Two large rivers (Indigirka and Kolyma) drain the eastern part of Sakha-Yakutia (E in Fig. 4.12) and deliver up to 80% of the total runoff, but generally freshwater inflow has limited influence on the coastal sea. The Indigirka River in its lower reach passes through easily-eroded quaternary rocks, carrying high loads of sediments (11.2×10^6 t yr^{-1}). The Kolyma River drains lowland areas and carries 8.2×10^6 t yr^{-1} of sediment. The main changes in natural waters can be attributed to dam construction, industrial effluents (gold mines and other non-ferrous metal mining complexes), agricultural and domestic wastes.

zone in the Arctic than in the western (the Baltic Sea coast) and southern areas (the Black, Azov, and Caspian Sea coasts).

The break-up of the former Soviet Union in the 1990s transformed much of Russia. The northern coastal regions now represent > 64% of the Russian Federation and thus, the resources, environmental, social and economic state of these regions has great significance for the future development of the country. The notion of environmental safety is particularly relevant to the Arctic for several reasons. Among these are concerns relating to the fragility of northern ecosystems and their vulnerability to human disturbance. In addition, the area has a profound influence upon global (or at least hemispheric) environmental processes such as atmospheric and oceanic circulation, global warming and ozone layer depletion resulting from drivers that originate from within and outside the area (e.g., a warming climate, change in the ice sheets).

Table 4.9. Russian Arctic. Links between coastal issues/impacts and land-based drivers; overview and qualitative ranking at regional/sub-continental scale. (Category: 1, low; 10, high. Trend: ⇒ stable, ⇑ increasing, n.o. not observed; *letters* for sub-regions refer to Text Box 4.7, Fig. 4.12)

Coastal impact/ issues	Anthropogenic drivers	Western Russian Arctic (WRA) coast[a]			Eastern Russian Arctic (ERA) Coast	
		Category	Trend-expectation	Sub-regions particularly affected	Category	Trend-expectation
Pollution	Industrialisation	5–10	⇑	White Sea (A), locally major, Arkhangelsk, North. Dvina (A2)	4–5	⇒/⇑
	Navigation	3–6	⇑	Barents Sea (B), locally major Kola Penin. (B1), Pechora R. (B2)	2–3	⇑
	Urbanisation	8–9 (locally)	⇑	Kara Sea (C), locally major, Ob R. (C2), Yenisey (C3) partly Lena R. (D4)	2–3	⇑
Acidification	Industrialisation	8–10	⇒/⇑	Northern Dvina (A2), Kola Peninsula (B2) Yenisey R. (C3)	3–4	⇑
Radioactive pollution	Nuclear industry/ Navy/nuclear-power/engineering	5–10	⇒	Kola Bay (B1), Guba Chernaya (south of Novaya Zemlya B2) Yenisey Bay (C3)	3–4	⇒
Erosion	Damming	2–4	⇒	Ob R. (C2), Yenisey R. (C3)	1	⇒
	Thermoabrasion[b]	6	n.o.	Laptev Sea coast (D)	6	n.o.
Sedimentation	Navigation	2–3	⇒		2–3	⇒
Loss of biodiversity	Fisheries/damming/ pollution	1–3	⇒		n.o.	

[a] The Lena River divides the Western Russian Arctic (WRA) and the Eastern Russian Arctic (ERA); which comprises the whole area east of the Lena Basin. This boundary crosses the Laptev Sea and demarcates the junction of the Eurasian and North American tectonic plates.
[b] Thermoabrasion is climate driven thus mentioned here to showcase its much bigger role as a driver as compared to human influence.

The administrative regions of the Russian Federation correlate closely with the large catchment basins allowing a sub-regional division relevant to the Arctic seas and an assessment of management responses within the existing administrative framework (Fig. 4.12; Text Box 4.7).

4.5.2 Assessment of Land-based Drivers, Pressures and Coastal Impacts

The Russian Arctic has a long history of resource use and development, but concerted pressure on the coastal zone started in the 1930s. River and marine transport routes remain the most important part of the Arctic infrastructure. Catchment basin use is variable in the Russian Arctic. Fisheries, forestry and reindeer breeding are being supplemented by the development of industrial production sectors such as metallurgic plants (e.g., Severonickel, Pechenganickel, Norilsk), mining extractive and mining concentrating industries (e.g., Apatit, Pechora-coal), and high-capacity oil and gas output complexes.

4.5.2.1 *Drivers and Pressures*

Because of prevailing sea currents and atmospheric conditions, the Arctic Ocean acts as a sink for a wide range of pollutants, including heavy metals, toxic substances, hydrocarbons, PCBs and nuclear wastes (Griffiths and Young 1990). In recent years, various projects have been launched to extract vast quantities of natural resources.

Generally, the river basins are under considerable pressure from populated and industrial areas, particularly to the west of the Yenisey River (Table 4.9, Fig. 4.13). Airborne and waterborne pollutants find their way to the Arctic via long-range transport pathways. The traditional economy of indigenous people based on renewable natural resources remains a feature of the Arctic region. However, the main pillar of current economic development can be found in diversified industrial use of non-renewable resources such as oil, natural gas, coal, minerals, raw materials, and rare and precious metals. The Arctic coastal environment is under growing pressure from both local industrial centres and traditional economies and changing horizontal and atmospheric flows of pollutants, water and sediments in large catchments.

4.5.2.2 *Coastal Issues – State Changes and Impacts*

Pollution

Among the most important pollutants in the Russian Arctic are heavy metals, oil products, sulphur and nitrogen oxides, and organic micropollutants. Air-borne wastes produced by metallurgy smelters, cement plants and mining, strongly affect natural ecosystems within several industrial regions in the Kola Peninsula, Arkhangelsk, Vorkuta and Norilsk areas and in the Murmansk region. The great Siberian rivers remain among the most pristine big rivers in the world (especially the Lena River); however, in their upper and middle reaches heavy metals concentrations may still be quite high.

Rivers and lakes within gas and oil extracting regions (mainly in eastern European and north-western Siberia) are heavily polluted by crude oil leading to significant changes in the diversity of local fauna. Persistent organic pollutants (POPs) are among regularly-detected substances in the water, sediments and biota of the Arctic region; mainly organochlorine pesticides (e.g., HCH) and their metabolites, industrial chemicals (PCBs) and anthropogenic and natural combustion products (dioxin/furans and PAHs).

Acidification

Anthropogenic acidification of waters is occurring due to sulphur dioxide and oxides of nitrogen deposition from the atmosphere on the watershed areas (e.g., in the Murmansk region). At the same time, the trans-boundary transfer of sulphur from the Western Europe (and even from the American continent) is a significant source of sulphur input in the Russian Arctic.

Radioactive Pollution

Sources of artificial radionuclides in the Russian Arctic Seas include: the Novaya Zemlya nuclear weapon tests (1950s and 1960s), global background from other tests, the Chernobyl accident, mining-chemical plants in Russia, radiochemical plants in Western Europe, dumping of solid and liquid radioactive wastes in the Barents and the Kara Seas, and the northern military marine and atomic icebreaker fleet. Located in the river basins, Russian chemical plants of military-industrial complexes are powerful sources of radioactive pollution of the seas, for example, 1 100 TBq (30 000 Ci) were transferred to the Arctic Ocean through the Ob and Yenisey rivers between 1961 and 1989. However, the general degree of water radioactive contamination of the Arctic seas differs little from background (~6 $Bq\,l^{-1}$), except for several localized areas.

Coastal Geomorphology

Damming is seriously affecting the erosion-accretion equilibrium in the basins of some big Arctic rivers; there are 13 dams and reservoirs in the Ob River basin (total volume 75.2 km^3), 8 dams and reservoirs in the Yenisey River basin (473.9 km^3) and a few dams with reservoirs in the Lena and Kolyma basins. The most important changes in the suspen-ded matter discharge have occurred in the Yenisey basin.

Coastal erosion due to thermo-abrasion is a significant source of sediment for the coastal zone (e.g., the total mass of abrasion material along 2 400 km of the Laptev Sea coastline is 2.4 times the discharge of riverine suspended sediment into the Laptev Sea). Erosion rates of high cliffs and seasonal ice melting causes shoreline retreat, and significant abrasion has been detected in the eastern White Sea and in the East Siberian Sea.

Eutrophication

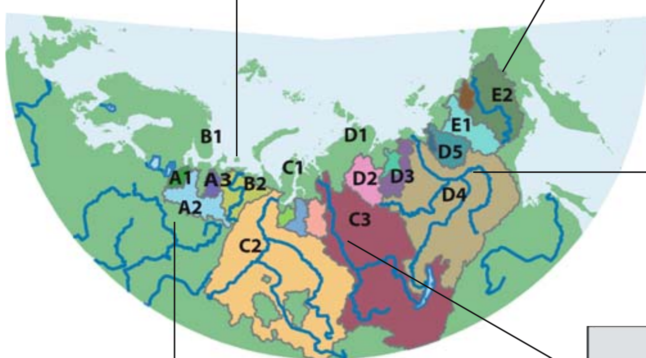
Despite the existence of anthropogenic drivers for excess nutrient supply, the hydrological and biogeochemical system settings regulating water formation in the Arctic basin may diminish the development of eutrophication. Characteristic signals of eutrophication that can be detected locally are diminishing dissolved O_2 concentrations, increasing nutrient concentrations, intensive al-

Table 4.10. Russian Arctic. Major activities, present status and trends affecting the coastal zone. (Trend: ⇒ stable, ⇑ increasing; *letters* for sub-regions refer to Text Box 4.7, Fig. 4.12)

Anthropogenic drivers	Major state changes and impacts	Present pressure status	Trend expectation	Sub-regions particularly affected
Industrialisation incl. mining, oil and gas production	Pollution/acidification	Medium/major	⇒/⇑	A2, B1, B2, C2, C3, D4
Navigation	Pollution Sedimentation	Medium Minor	⇑ ⇒	A2, B2, D4, D5 (minor in all other areas)
Nuclear-power, engineering, nuclear industry, Navy	Radioactive pollution	Minor (major locally)	⇒	B1, B2, C3
Urbanisation	Pollution/partly eutrophication	Minor (medium to major locally)	⇑	A2, WRA Coast
Damming	Coastal erosion	Minor (locally more important)	⇒	C3, E2

Sub-region (B) · Barents Sea; Kolsky Peninsula (B1), Pechora River (B2)			
Drivers	**Major coastal impact**	**Present pressure status**	**Trend expectations**
Industrialisation/ urbanisation (locally)	Pollution	Major	⇑
	Acidification (particular B1)		⇒
Nuclear-power engineering, nuclear industry, Navy	Pollution (radionuclides, particular B1, Guba Chernaya south of the Novaya Zemlya)	Major	⇒
		Medium	
Navigation	Pollution/ sedimentation	Minor	⇒
		(locally medium)	⇑

Sub-region (E) · East Siberian Sea, Indikirka River (E1), Kolyma River (E2)			
Drivers	**Major coastal impact**	**Present pressure status**	**Trend expectations**
Industrialisation	Pollution/ acidification	Minor	⇒
		(locally Medium)	⇑
Urbanisation	Pollution	Minor	⇑
Navigation	Pollution/ sedimentation	Minor	⇒
			⇑
Damming	Erosion	Minor	⇒



Sub-region (D) · Laptev Sea, Taymyr Peninsula (D1), Kathanga River (D2), Olenek River (D3), Lena River (D4), Yana River (D5)			
Drivers	**Major coastal impact**	**Present pressure status**	**Trend expectations**
Thermoabrasion[a]	Erosion	Medium	**n.o.**
Industrialisation/ urbanisation (locally)	Pollution	Medium (locally increasing)	⇒
			⇑
Navigation	Pollution/ sedimentation	Minor	⇒
		(locally medium)	⇑
Damming	Erosion	Minor	⇒

[a] Thermoabrasion is not a human driver but listed due to its important role generating coastal erosion.

Sub-region (A–A2) · White Sea; Northern Dvina River and Archangelsk			
Drivers	**Major coastal impact**	**Present pressure status**	**Trend expectations**
Urbanisation	Pollution	Major	⇑
Industrialisation	Pollution	Major	⇑
	Acidification (particular Archangelsk)		⇒
Navigation	Pollution (particular Northern Dvina)	Medium	⇑
	Sedimentation	Minor	

Sub region (C) · Kara Sea, Yamal Peninsula (C1), Ob River (C2), Yenisey River (C3)			
Drivers	**Major coastal impact**	**Present pressure status**	**Trend expectations**
Industrialisation	Acidification	Medium	⇒
		(locally major)	⇑
Nuclear-power engineering, nuclear industry, Navy	Pollution (radionuclides)	Medium	⇒
		(locally major)	
Urbanisation	Pollution	Medium	⇑
		(locally major)	
Damming	Erosion	Minor	⇒
Navigation	Sedimentation	Minor	⇒

Fig. 4.13. Russian Arctic. Sub-regional synthesis and typology of river catchment–coast interactions

gae bloom with prevailing blue-green and green phytoplankton species. However, the periodicity of appearance of low dissolved oxygen in waters of big Arctic river basins is very low. In general, eutrophication is significant in some small rivers and reservoirs but is not a major issue for the big Arctic rivers and their receiving water bodies.

Biodiversity and Harvestable Resources

Increasing pollution of lakes, rivers and the coastal zones of Arctic seas by oil products, heavy metals, pesticides and other pollutants is leading to loss of biodiversity including reduction of biomass and structural change in the planktonic community, loss of biomass and diversity of bottom fauna and, especially, loss of habitats and significant loss of fisheries. Overfishing exacerbates land-based pressures and significant decreases of fish populations results in a reduction of numbers of birds, seals and walruses.

4.5.3 State Changes, Impacts and Future Trends

Pollution by petroleum products, heavy metals and organic micro-pollutants remains the most significant problem in the Russian Arctic (Table 4.10). The economic recession of the 1990s in the Russian Federation interrupted further increases in pollution in the industrialised western Arctic. However, increasing activity by national and multinational oil, gas and coal companies will require extended infrastructure for land transport and growing navigation across the region. A significant increase in related pressures on the environment is anticipated.

Acidification is a major issue in some local areas of the Kola Peninsula, the Archangelsk and Norilsk areas; at present, there is stabilisation or even a decrease in sulphur deposition. Elsewhere, acidification is of minor importance.

Radionuclide pollution of the Arctic environment remains a major concern. Maximum pollution occurred in the 1960s and 1970s during and after the period of nuclear weapons tests. There are indications of a stabilisation of the situation, but due to the long life span of many nuclides the problem will persist into the future.

In the former Soviet Union many large dams were constructed in Arctic river basins. However, significant influences of damming on the annual hydrological regime and suspended matter discharge rates were observed only in the Yenisey River. For example, after construction of the Krasnoyarskaya dam in 1967, suspended matter discharge decreased by 2–3 times.

Generally, water withdrawal is not an issue in the Arctic, reflecting the high volumes of river water discharge and relatively low regional consumption of fresh water. Predictions to 2025 indicate that the total water withdrawal from Arctic river basins and loss by evaporation from reservoirs would not exceed 1–2% of the river runoff.

4.5.4 Conclusions – Russian Arctic

In the Russian Arctic the most important coastal issues relate to pollution originating mainly from industrialisation and navigation, acidification, radioactive pollution and erosion. In the Arctic basin there are many small rivers draining to the coastal seas and, due to the low density of population, the overwhelming majority of them, with the exception of small rivers of the Kola Peninsula and probably of the White and Barents seas, are relatively pristine. Figure 4.13 is a sub-regional synthesis of main river catchment-coastal change issues, and provides an expert judgement-based ranking and trend analysis.

4.6 Europe – Catchment-Coast Interactions

Regional assessment and synthesis efforts in Europe started in the late 1990s, incorporating both natural and social science aspects of catchment–coast interactions and in particular focused on policy and plausible scenarios of change. The EuroCat project provides primary information on the Vistula, Elbe, Rhine, Humber, Seine, Po, Idrija, Axios, and Provadijska catchment-coast systems (*http://www.iia-cnr.unical.it/EuroCat/project*) and the daNUbs project on the Danube–Black Sea interaction (*http://danubs.tuwein.ac.at*). A key consideration in these and related projects was to provide an appropriate coverage of the major European coastal sub-regions (Fig. 4.14) and in there to select catchments representative of a certain type of coast under typical driver–pressure settings. The increasing interest of the public sector on integrated catchment-coast studies is evident from the large-scale study on heavy metals and organic pollutants in the Rhine catchments and their impact on sediment quality in the coast (Text Box 4.8).

Both the "EuroCat" (*http://www.cs.iia.cnr.it/EUROCAT/project.htm*) and "daNUbs" (*http://danubs.tuwien.ac.at/*) project are part of the ELOISE (European Land-Ocean Interaction Studies; Cadée et al. 1994, *http://www2.nilu.no/eloise/* and for the digest: *http://www.eloisegroup.org/themes/*) research initiative of the European Union. Since the early 1990s the EC's ELOISE has developed into the biggest regional project cluster within LOICZ and accommodated around 60 individual multinational projects. As part of this initiative a major workshop in 2003 focused on DPSIR and scenarios for future developments of European coastal seas (Vermaat et al. 2005); the pertinent results of the workshop are incorporated in this section.

The work in EuroCat extended the DPSIR approach (see Text Box 4.1 above) with the development of scenarios highlighting potential catchment–coast interactions under different world views. Before addressing these scenarios and providing case applications (see Sect. 4.7), a

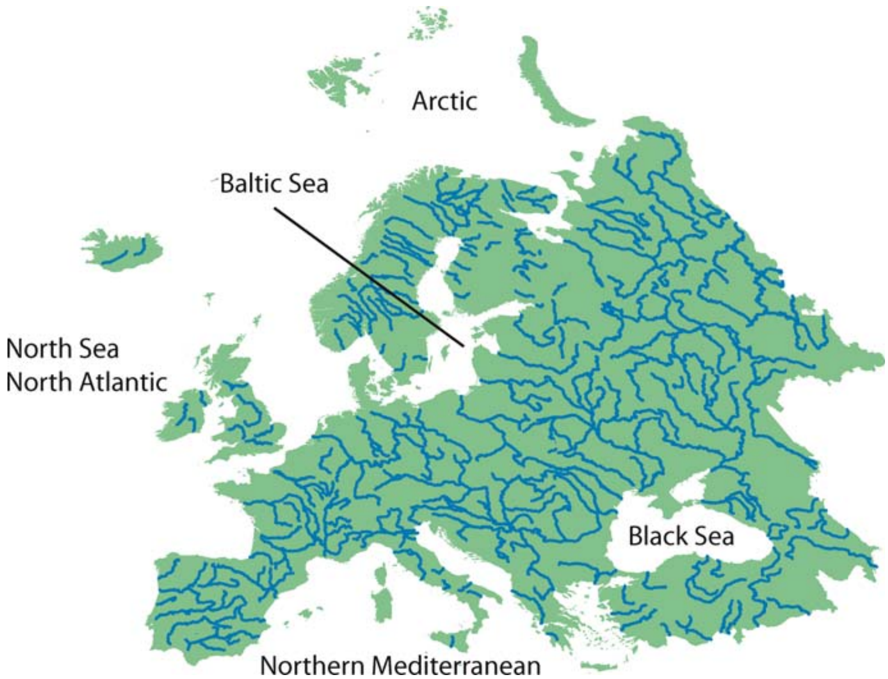


Fig. 4.14. Europe. The sub-regions identified in the European Basins workshops

brief summary of the key findings from EuroCat is given to allow comparison with the regional assessments described earlier. Relatively rich data and information sources have underpinned this European assessment and yielded an extended coastal basin and catchment typology (Meybeck et al. 2004a).

4.6.1 Overview of the European Coastal Zone/Catchment Systems

Europe's coastal zone is to a considerable extent characterised by enclosed or semi-enclosed seas that largely trap the land-based inputs (e.g., Black Sea, Mediterranean Sea, Adriatic Sea, Baltic Sea, Fig. 4.14). In the North Sea, riparian influences affect the immediate near-shore coastal zone, but overall the system functioning is more ocean-dominated (Thomas et al. 2004). Other areas, such as the rocky and mountainous shores of the Atlantic coast of Scandinavian or the Iberian peninsula with its relatively small shelf, are even more ocean-dominated.

The median length of the river catchments in Europe is 600 km (ranging from 200 to 2 200 km) with the Danube, at 2 200 km, being rather modest in a global comparison. Processes in the catchment affect the coast with a certain delay time. Runoff per coastal catchment ranges from 20 and 715 mm yr^{-1} (Fekete et al. 1999, 2001, Vörösmarty et al. 2000a,b). Specific discharges range from 2 to 45 l s^{-1} km^{-2}, which is moderate compared to other global regions.

Seasonal runoff in Europe to a large extent is of the pluvial–oceanic type with peak flows during winter (e.g., the major rivers draining to the Atlantic coast), although some such as Rhine and Elbe have more complex cycles due to the influence of lakes and mountains. Northern European rivers have a minimum flow in late winter while Mediterranean rivers are more variable, ranging from minor or even zero net flow in summer to those (e.g., Rhone and Po) with mountain influences similar to the Rhine and Elbe.

Sediment yields differ markedly among sub-regions of Europe. Estimates from Meybeck et al. (2004b) show the lowest rate in the Baltic (12.5 t km^{-2} yr^{-1}) and the highest in the northern Mediterranean (300 t km^{-2} yr^{-1}), with relatively low to medium rates elsewhere (i.e., Atlantic 131 t km^{-2} yr^{-1}, northern Black Sea and Arctic 48 t km^{-2} yr^{-1}, North Sea 38 t km^{-2} yr^{-1}). However, sediment loads to the coastal seas are determined to a large extent by flow regimes modified by impoundments and irrigation (see below).

4.6.2 Assessment of Land-based Drivers, Pressures and Coastal Impacts

There are pronounced differences among the sub-regions of Europe in the type and intensity of drivers and pressures and the resultant impacts on coastal systems (Fig. 4.15).

4.6.2.1 *Population Pressure and Development (Urbanisation along River Catchments and in the Coastal Zone)*

Europe's population has grown by 100 million since 1972, totalling 818 million in 2000 (13.5% of the global total).

Text Box 4.8. Contaminated sediments in estuaries: the port of Rotterdam

J. Grandrass

Most of the river-borne sediment is deposited in the estuarine zone, and only a relatively small proportion of the fine sediment load eventually reaches the open coastal zone, where it eventually settles. In areas with limited tidal range and little or no off shore currents (such as the Mediterranean and Baltic seas) most of the sediment in the estuaries and deltas are of river origin. In estuaries with large tides this balance of sediments is reversed and there is a very little export of fluvial material but a net trapping of material originating from coastal and marine erosion. This net trapping of sediment from the marine environment results in major dredging activities to allow for continued access of waterways to shipping. It has been estimated that dredging activities to remove sediments in the North Sea region exceed sediment transport by the rivers.

Continuous maintenance dredging is essential in the Port of Rotterdam, the largest port in the world. Marine sediments accumulate through tidal action in the western port areas, while the eastern port sections receive fluvial sediments transported by the Rhine. The sediment transport of the Rhine is in the order of 3–4 × 10^6 tonnes dry weight per year, of which roughly half is deposited in the port and the remainder is transported to the North Sea. To maintain adequate port facilities, 15–20 × 10^6 m^3 of sediments are dredged per year. The relocation of this dredged material to the North Sea, the preferred disposal option, is regulated by a set of so-called Sea/Slufter limit values. Dredged material exceeding these limits, mainly sediments from the eastern port areas, has to be disposed of in a confined site, the Slufter (Fig. TB4.8.1).

This storage area has a limited life and the Port Authority of Rotterdam posed the question of how the contamination of dredged material will develop in the future and whether it will reach levels that allow again its relocation to the North Sea. This required (*a*) the development of an integrated modelling tool for contaminant (heavy metals and organic micro-pollutants) transport at the catchment level linked to the quality of sediments in the Port of Rotterdam and point and diffuse sources in the transboundary Rhine catchment and (*b*) the development of scenarios. Two types of scenarios were modelled, taking the present state as a starting point, for the time-period until 2015. The "business as usual" (BAU) scenarios take measures into account which are already agreed on or are "in the pipeline", i.e., the implementation can most probably be expected. The "Green" scenarios include additional reduction measures that might be realised but largely depend on future policies. Taking the present state as a starting point, the changes in modelled future inputs in the Rhine basin were extrapolated on the development of the quality of sediments in the eastern parts of the Port of Rotterdam and were compared with Dutch quality criteria (2002) for relocation of dredged material to the North Sea.

Measures accounted for in the BAU scenarios are not expected to result in a substantial decrease in contamination of sediments/dredged material for most of the investigated substances. Additional measures (Green scenarios) could achieve more satisfying results. However, even in the Green scenarios, defined target values will still be exceeded for the investigated compounds until 2015, with the exception of lead (Fig. TB4.8.2). Pathways incorporating the highest reduction potentials for copper, zinc and cadmium are inputs from urban areas, from wastewater treatment plants and to a lesser extent erosion from agricultural ar-

Fig. TB4.8.1.
The Slufter (Rotterdam) – a confined disposal site for contaminated dredged material (from Gandrass and Salomons 2001)

The most significant demographic trends that bear on changes in the coastal zone include the increasing number of households and the increasing mobility of people. While the coastal zone of Europe has areas (particularly in highly industrialised Western Europe) with medium to high population densities (> 500 people km^{-2}), there are also remote areas in the Arctic and northern Baltic with low population densities (0–5 people km^{-2}). The population densities (people km^{-2}) in European sub-regions has been estimated as: North Sea (183), northern Mediterranean Sea (121), Atlantic (88), northern Black Sea (78), Baltic (48), Arctic (6.6) (Meybeck et al. 2004a). Population density changes seasonally; during the summer tourist season population more than doubles in parts of the northern Mediterranean coast.

The expansion of buildings and infrastructure has multiple causes, but two factors are especially relevant for coastal areas - transportation and tourism. Europe's coasts host 66% of the total tourist trade and in the Mediterranean, for example, arrivals are expected to grow from 135 million per annum in 1990 to as many as 353 million by 2025. Tourism's main environmental impacts are also generated via transport requirements, together with use of water and land, energy demands and waste genera-

◀

eas. Additional related measures, which would bring the highest net reductions, are substitution of building materials as uncoated galvanised steel and copper, decoupling of paved urban areas from sewer systems, enlargement of rainwater storage basins and erosion reduction measures in agricultural areas.

PAHs are mainly released by combustion of fossil fuels and related processes resulting in elevated atmospheric deposition rates in urban areas. This pathway and related additional measures, especially towards reduced emissions from residential combustion, incorporates the highest reduction potential. PCBs have been banned in many countries and are restricted in marketing and use by the European Council Directive 76/769/EEC. New PCB inputs are mainly driven by atmospheric deposition; re-emissions from soils becoming more important. Major pathways are paved urban areas and direct atmospheric deposition on surface waters. Additional reduction measures are decoupling of paved urban areas from sewer systems and enlargement of rainwater storage basins.

An issue of special importance is the "historic" contamination of sediments in the Rhine basin. Contaminated sediments ("legacy" of past pollution) are stored behind dams in the Rhine catchment. They are already eroded by high discharge episodes and affect the quality of the sediments in the Rhine estuary. Not only in the Rhine but also in other catchments with past industrialisation, this process which might become more important in the future (i.e., with climate change).

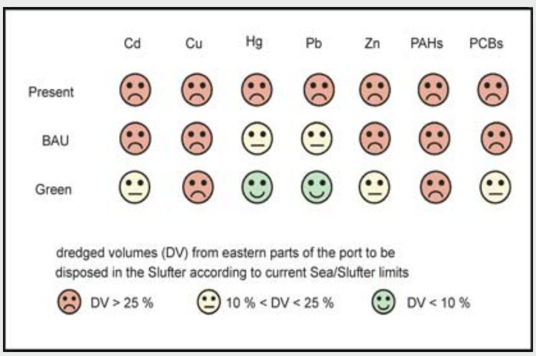


Fig. TB4.8.2. Present and estimated future quality of dredged material in the eastern parts of the Port of Rotterdam according to Dutch Sea and Slufter limit values

tion. The environmental impacts are highly concentrated and seasonal within or close to resort areas, but lateral expansion along coastlines is also a common phenomenon. Road transport is the dominant mode in Western Europe, with rail networks somewhat better developed; the balance of central investments continue to favour road transport; for example, between 1992–2000 the European Investment Bank gave 50% of its loans to road projects and only 14% to rail (EEA 2003). Transport infrastructure and trade are strongly linked, and coastal habitats and ecosystems face fragmentation along with other areas close to main arterial transport routes.

All European countries are engaged in growing and extensive trade activities placing pressure on coastal localities. Maritime transport accounts for 10–15% of total SO_2 emissions and in the Mediterranean, oil spills and related risks are high reflecting that 30% of all merchant shipping and 20% of global oil shipping crosses that sea each year. Ports and associated industrial development are responsible for land conversion/reclamation, loss of intertidal and other habitats, dredging and contaminated sediment disposal.

4.6.2.2 *Changes in Flow Patterns*

The increasing physical growth of European economies manifests itself, among other ways, in massive new construction of buildings and infrastructure that has profound effects on catchment processes, leading to increased flood risk, changes in sediment fluxes (and contamination risks) as well as habitat and biodiversity loss in the catchment-coast continuum. Direct physical alteration and destruction of habitats because of development pressure is, along with nutrient pollution, probably the most important threat to the coastal environment both for Europe and worldwide (GESAMP 2001).

Changes in flow regimes of European rivers are a key pressure on the systems and affect substantially the interaction with the receiving coastal waters. In particular in the northern Mediterranean basins, sediment and nutrient flows to the coastal zone have largely been altered by damming and water diversion and use. Rivers and deltaic areas such as the Po, Rhone and Ebro, have suffered from sediment starvation in response to significant hydrologic changes in the catchments.

In addition, irrigated cropland is a large proportion of the agricultural areas in Western, Central and Eastern Europe, (see *http://countries.eea.eu.int/SERIS/NavigateCurr*, for border of these regions) ranging from 11% to 18%, and continues to expand in some Western European and Mediterranean areas. This type of production affects water resources and wetlands in particular because 31% of Europe's population already lives in countries that use more than 20% of their annual water resource (EEA 2003).

Meybeck et al. (2004b) estimated that the overall freshwater riverine discharge to the Mediterranean Sea has diminished by almost 50% since the beginning of the 20th century, from 600 $km^3 yr^{-1}$ to 330 $km^3 yr^{-1}$; the outstanding example is the Nile with almost 95% reduction of flow (see also Sect. 4.3, above). Effects of flow change are evident in the horizontal transport of organic carbon and pollutants. The Mediterranean shows a slower increase in nutrient loads than expected from the population pressure, but the delivery of population-driven nutrient loads to the coastal zone below the Aswan dam now equals the loads before damming in the early 1960s (Nixon 2003).

4.6.2.3 *Nutrients*

Europe's semi-enclosed and enclosed seas, with their limited water exchange, are particularly sensitive to pollution threats. Marine and coastal eutrophication from elevated nitrogen and phosphorus levels quickly emerged as a worrying trend, the impacts of which were exacerbated by the loss of natural interceptors such as coastal wetlands. Severe eutrophication has occurred in the Black Sea and in more enclosed areas in the Baltic and Mediterranean seas.

Meybeck at al. (2004a), based on the modelling data of Green et al. (2004), calculated between 0.5 and 4.5 mg l^{-1} total nitrogen for remote riverine areas such as the Norwegian basin (principal rivers: Trondheims Fjord, Soge Fjord, Alta R.) and the North Sea basin (principal rivers: Rhine, Elbe, Gota, Glama, Weser, Meuse, Thames and Humber) respectively. Average total N (i.e., NO_3^-, NO_2^-, NH_4^+ and organic N) calculated per coastal catchment contained in the 5-degree grid cell database, yielded values ranging between 2 437 and 178 kg N km^{-2} yr^{-1} in the western parts of the UK and Sweden, respectively. This represents a 10- to 20-fold difference across Europe.

In summary, there is a northwest to south-central axis of high nitrogen yields, covering the UK, Western and Central Europe (i.e., the North Sea catchment basin) including parts of Scandinavia, Benelux, Germany and Italy wherein values ranged between 1 445 and 2 437 kg N km^{-2} yr^{-1}. Countries bordering the Atlantic basin, the southern Baltic, the Black Sea and eastern Mediterranean yielded an order of magnitude less, with values between 500 and 900 kg N km^{-2} yr^{-1}.

Obviously differences exist in the effects on water quality and ecosystem functioning along this north-south axis. Usually dissolved organic nitrogen (DON) originating from more remote and low-populated areas, such as the Arctic, has little effect on the phytoplankton system in comparison to the dissolved inorganic nitrogen (DIN)-rich loads – essentially ammonium and nitrate – from highly-populated and agricultural areas. Nitrate represents > 90% of the total N load in Western European rivers, such as the Scheldt. Meybeck et al. (2004b) consider Europe to be at the upper end of the nitrogen yield values for global regions (also see Text Box 3.1, Chap. 3).

Over the last 20 years, nutrient yields (especially phosphorus) have greatly decreased for both the Rhine and Elbe and today, the main sources of nutrient discharge follow diffuse pathways mainly nourished by agriculture. These intensive measures to control point source discharges have helped towards achieving the targets that were defined by the conference of Environmental Ministers in the early 1980s (to accomplish a 50% reduction of nutrient inputs to the North and Baltic Sea between 1985/87 and 1995; Behrendt et al. 2002) for phosphorus but not for nitrogen, where the reduction in specific yields is between 36% and 48% on a catchment scale. At the coastal interface the total load reduction to the three major coastal seas ranges between 12% and 26% (Table 4.11).

The importance of diffuse rather than point sources was apparent even in the early 1990s in the Vistula and other Eastern European rivers such that their status compares with that currently of the Rhine and Elbe after management action has been taken. Different hydrologic conditions, lower population density in the catchment and limited access to waste water treatment facilities all result in a higher proportion of nutrient input from diffuse sources. As a consequence of agricultural pressure and limited water treatment, the nutrient loads of the Po into the Adriatic Sea also are clearly dominated by diffuse sources. Waste-water treatment levels and discharges are still problematic in the Mediterranean, Adriatic and Black seas.

Irrespective of the fact that LOICZ Basins (as a work in progress) in its first years did not generate a comprehensive assessment and synthesis of the situation in North America which makes it somewhat difficult to compare the European situation at least two case studies from North America are provided. The Hudson River system (Text Box 4.9) and the Mississippi River system (Text Box 4.10) may help putting the European findings

Table 4.11. Europe. Total nitrogen and phosphorus inputs to three European coastal seas and the changes between 1983–87 and 1993–97 (after Behrendt et al. 2002)

Coastal sea	Period	Total N inputs (kt yr^{-1})	Diffuse sources (%)	Change in total N between the two periods (%)	Total P inputs (t yr^{-1})	Diffuse sources (%)	Change in total P between the two periods (%)
Black Sea	1983–1987	150.4	75.0		10 640	36.7	
	1993–1997	131.7	80.5	–12.5	5 310	71.6	–50.1
North Sea	1983–1987	873.1	56.6		78 770	31.0	
	1993–1997	642.1	69.1	–26.5	30 320	65.0	–61.5
Baltic Sea	1983–1987	61.1	74.8		4 130	30.3	
	1993–1997	44.9	81.1	–26.6	1 620	71.0	–60.8

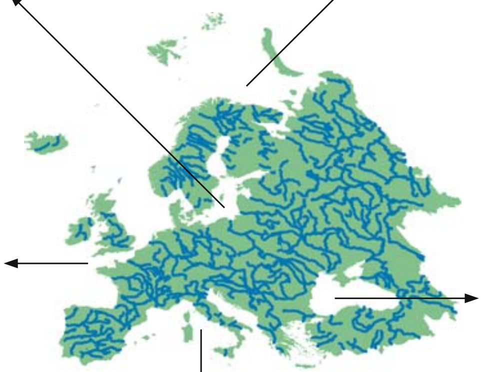
[a] Station Bimmen/Lobith at the German-Dutch Border.

Sub-region: Baltic Sea; a) Southern Baltic; b) Bothnian Bay c) Gulf of Finland			
Drivers	**Major coastal impacts**	**Present pressure status**	**Trend expectations**
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/ sewage)	Medium	⇑
		locally major	⇒
Agriculture	Eutrophication	Medium	⇒
		locally major	
Industrialization/ mining/ dredging	Pollution including Pollution heritage	Medium	⇒
		locally major	
River regulation/ navigation	Erosion/ flooding	Medium	⇒
		locally major	⇓
Damming/ water abstraction	Reduced water flow/ erosion	Minor	⇒

Sub-region: Arctic; a) Norwegian Basin; b) Barents Sea			
Drivers	**Major coastal impacts**	**Present pressure status**	**Trend expectations**
Industrialization/ mining/ dredging	Pollution including Pollution heritage	Medium	⇑
		locally major	⇒
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/ sewage)	Minor/ medium	⇑
		locally major	⇒
River regulation/ navigation	Erosion/ flooding	Medium	⇒
Agriculture	Eutrophication	Minor	⇒
Damming/ water abstraction	Reduced water flow/ erosion	Minor	⇒

Sub-region: North Atlantic/ North Sea; a) Iberian-Biscay Plains; b) Hutton-Rockall Basin c) North Sea			
Drivers	**Major coastal impacts**	**Present pressure status**	**Trend expectations**
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/ sewage)	Major	⇒
			⇓
Agriculture	Eutrophication	Major	⇒
		Medium	⇓
Industrialization/ mining/ dredging	Pollution including Pollution heritage	Medium	⇓
		locally major	
River regulation/ navigation	Erosion/ flooding	Medium	⇒
		locally major	⇓
Damming/ water abstraction	Reduced water flow/ erosion	Minor	⇒

Sub-region: Black Sea; a) Azov Sea; b) North Western Black Sea			
Drivers	**Major coastal impacts**	**Present pressure status**	**Trend expectations**
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/ sewage)	Medium	⇑
		locally major	⇒
Agriculture	Eutrophication	Medium	⇒
		locally major	⇓
Industrialization/ mining/ dredging	Pollution including Pollution heritage	Medium	⇒
		locally major	⇓
River regulation/ navigation	Erosion/ flooding	?	
Damming/ water abstraction	Reduced water flow/ erosion	?	



Sub-region: North Mediterranean; a) West Aegean Sea; b) North Ionian Sea; c) Adriatic Sea; d) Tyrrhenian Basin; e) Balearic Basin			
Drivers	**Major coastal impacts**	**Present pressure status**	**Trend expectations**
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/ sewage)	Major (seasonal tourism!)	⇑
Damming/ water abstraction	Reduced water flow/ erosion	Major	⇑
			⇒
Agriculture	Eutrophication	Medium	⇒
		locally major	
Industrialization/ mining/ dredging	Pollution including Pollution heritage	Medium	⇒
		locally major	
River regulation/ navigation	Erosion/ flooding	Medium	⇒
		locally major	

Fig. 4.15. Europe. Sub-regional synthesis and typology of the river catchment–coast interactions

Text Box 4.9. The Hudson River estuary: a history of expanding and changing human pressures

Dennis P. Swaney and Karin E. Limburg

The Hudson River, whose 35 000 km^2 watershed occupies most of northeastern region of New York state as well as areas of adjoining states, spans a range of land cover from the forested Adirondack mountains to urban Manhattan (Fig. TB.4.9.1). The watershed is conveniently divided into 3 or 4 subregions, including the relatively heavily forested Upper Hudson, the agricultural Mohawk, the rural but increasingly suburban Middle Hudson, and the urban/suburban Lower Hudson. The river is dammed below its confluence with the Mohawk at Troy, just above Albany, and the dam serves as the upper boundary of tidal influence. Since the arrival of Henry Hudson (the first European to explore the Hudson) in 1609, the region has seen first gradual, and then in the 19th and 20th century, explosive population growth. This has brought significant and multifaceted aspects of human accelerated environmental changes to the estuary.

As the region was settled, vast areas of the Hudson basin were cleared of forest and replaced with crop and pastureland. Agricultural land use peaked early in this century. Some simulation results suggest that soil erosion, and the associated sediment and organic carbon flux to the river, may have peaked around the same time, possibly driving the metabolism of the river to its greatest level of heterotrophy (Swaney et al., 1996; Howarth et al., 2000a). Much of the agricultural land of that time has since been abandoned, returning to forest, or has been developed as the population expands outward from village and city centers.

In modern times, the regional population, especially that of the greater metropolitan area of New York City at the mouth of the Hudson, and the Hudson Valley extending up the river to Albany, has represented a major source of sewage and nutrient loads to the estuary, though the time series of individual constituents has varied depending upon the goals of waste treatment. Estimated BOD load peaked in the 1930s at about 600 metric tons d^{-1}, declining since then in response to improvements in sewage treatment to the present 100 metric tons d^{-1} (Hetling et al., in press). Total nitrogen load climbed steadily from the turn of the century to the 1930s to about 120 metric tons N d^{-1}, but has fluctuated at relatively high levels since that time, to the recent estimates of greater than 100 metric tons d^{-1} (Hetling et al., in press). Until recently, nitrogen removal has not been a priority sewage treatment practice. Total phosphorus load, on the other hand, peaked in the 1970s at about 35 metric tons d^{-1}, falling dramatically thereafter in response to sewage treatment and especially as phosphates were removed from detergent formulations as mandated by increasingly stringent environmental legislation regarding phosphorus (Hetling et al. 2003).

Over the years, the Hudson has felt other human impacts as well, including many forms of industrial pollution. Though most of these sources have been cleaned up in response to environmental legislation, there is still a legacy of PCB contamination in the sediments of the upper Hudson. Recent (and controversial) action by the EPA has mandated that these sediments be dredged from the river bottom and removed. Heavy metal and organic chemical contaminants also remain in the many of the coastal marshes and sediments of the lower Hudson and New York Harbor.

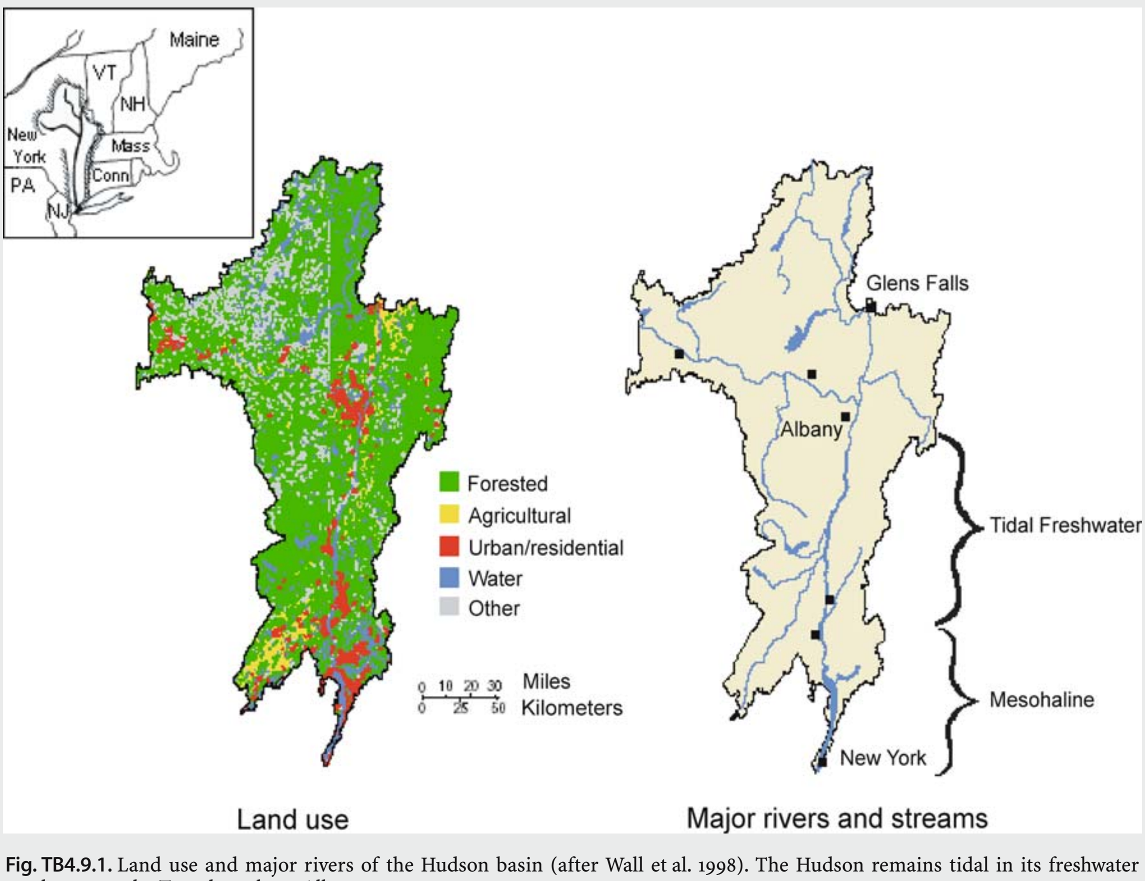


Fig. TB4.9.1. Land use and major rivers of the Hudson basin (after Wall et al. 1998). The Hudson remains tidal in its freshwater reaches up to the Troy dam above Albany

◀

The Hudson has also seen its share of harmful invasive species – on average, a new one per year has been observed over the last century (Mills et al., 1997) – including the devilishly-spiked water chestnut, *Trapa natans*, which now infests the marshes of the tidal freshwater Hudson, and perhaps most significant, the zebra mussel, (*Dreissena polymorpha*), which seems to have dramatically altered the carbon budget of large reaches of the freshwater estuary (Fig. TB.4.9.2).

While salinity eliminates the direct effect of *Dreissena* on the mesohaline Hudson, the interaction of high nutrient loads and physical circulation suggest that it is a highly eutrophic system in which productivity will continue to depend on upstream sources, local waste loads, and climate change-induced fluctuations of flow and stratification (Howarth et al. 2000b). Thus, the combined effects of human activities, waste loads, invasive species, and climate change will play a role in the nutrient loads of the Hudson system to the coastal zone.

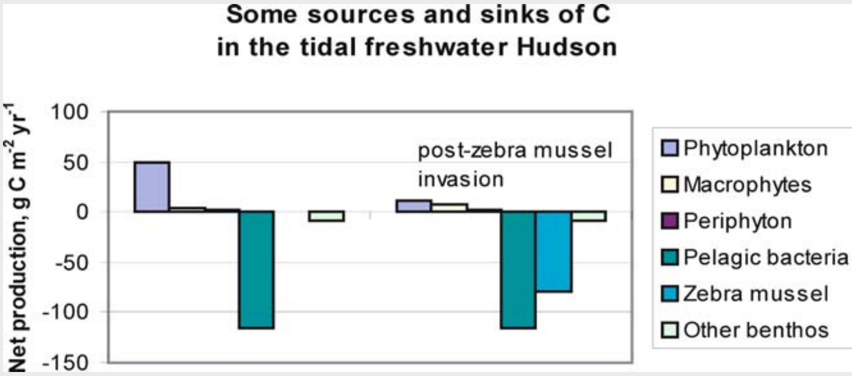


Fig. TB4.9.2. Effects of the invasion of zebra mussel (*Dreissena polymorpha*) on the carbon dynamics of the tidal freshwater Hudson (Cole and Caraco, in press)

of river catchment-coast interactions, their history and drivers into a broader geographical context. These cases together cover already more than 40% of the whole US drainage basin area affecting the Atlantic and Gulf of Mexico coastal waters.

4.6.3 Conclusions – Europe

The population pressure in the catchment basins connected to the North Sea/Atlantic sub-region dominates compared with the rest of Europe. Representing only 23.4% of the total area, this sub-region accommodates almost 41% of the population and contributes 48% of the total nitrogen emissions (5.5 times higher than in the Arctic and with a much higher bioavailability to coastal metabolic systems). The key drivers are urbanisation (not only coastal) and agricultural land use that employs large amounts of industrial fertilisers. The population density in this sub-region and in the northern Mediterranean is among the highest globally, ranging from 131 people km^{-2} to 120 people km^{-2} respectively. The Baltic (48) and the northern Black Sea (78) have lower population densities, and the Arctic (6.6) sub-region is sparsely populated. However, the assessment of current driver/pressure settings and trend expectations in the north-western Arctic (see Sect. 4.5 above) indicates that pressures due to urbanisation and raw material exploitation are likely to increase. Table 4.12 shows a summary of the key catchment-based driver/pressure interlinks with coastal impact and change. The trends, based on expert judgement, reflect the current expectations and in the nutrient case, they are substantiated by the quantitative findings of the ELOISE projects: EuroCat and DaNUbs.

In the Mediterranean sub-region, water abstraction and damming have had the most pronounced effect on coastal systems due to flow reduction. Around 50% reduction in water flow has diminished the expected acceleration of nutrient loads to the coastal zone and greatly diminished the sediment supply to the coastal systems.

In Europe significant progress has been made in combating point-source pollution of rivers, streams, estuaries and coasts (e.g., from sewage treatment plants and industrial facilities). As such, there has been a significant reduction in heavy metals, phosphorus and organic micro-pollutants discharges from rivers into the European coastal seas. However, with regard to nutrients (and in particular nitrogen), the issue of eutrophication remains and in some cases toxic algal blooms occur in Europe. From assessment of most coast systems in Europe, the EuroCat project concluded that eutrophication and in one case pollution (metals) were the major issues for the coastal zone. The results showed that even for the most stringent and plausible environmental protection scenarios, eutrophication will remain a problem affecting the ecosystem and economic resources (e.g., tourism, mussel farming). Strategies to combat eutrophication – managed retreat and/or wetland creation schemes, improved water treatment programmes, agricultural zoning – were much more effective in the UK and the Netherlands. An additional benefit of coastal realignment,

Text Box 4.10. Watershed alterations and coastal ocean response: the Mississippi River

Nancy N. Rabalais

The linked Mississippi/Atchafalaya River and northern Gulf of Mexico system is a prime example of the worldwide trend of changing river-borne fluxes and resulting diminution of coastal water quality. The Mississippi River system ranks among the world's top ten rivers in length, freshwater discharge, and sediment delivery and drains 41% of the contiguous United States (Milliman and Meade 1983; Fig. TB4.10.1).

One third of the flow from the Mississippi River main stem is diverted into the Atchafalaya River where it joins the Red River for eventual delivery through a delta 210 km west of the main Mississippi River birdfoot delta. Prevailing currents from east to west move most of the freshwater, suspended sediments and dissolved and particulate nutrients onto the Louisiana and Texas continental shelf (Rabalais et al. 1996). At the terminus of this river system is the largest zone of oxygen-depleted coastal waters in the western Atlantic Ocean (Rabalais et al. 2002).

The Mississippi River system delivers an average of 580 km^3 of freshwater to the Gulf of Mexico yearly along with sediment yields of 210×10^6 t yr^{-1}, 1.6×10^6 t yr^{-1} nitrate, 0.1×10^6 t yr^{-1} phosphorus and 2.1×10^6 t yr^{-1} silica (Turner and Rabalais 1991). The 1820–1992 average discharge rate (decadal time scale) for the Mississippi River is remarkably stable near 14 000 $m^3 s^{-1}$ despite significant interannual variability and some decadal trends (Fig. TB4.10.2). The discharge of the Atchafalaya increased during the period 1900–1992, primarily as a result of the tendency for the Atchafalaya to capture more of the flow of the Mississippi (until stabilized at 30% in 1977) (Bratkovich et al. 1994). A slight increase in Mississippi River discharge for 1900–1992 is accounted for by an increased discharge in September through December.

Mississippi River nutrient concentrations and loading to the adjacent continental shelf changed dramatically during the last half of the 20th century. The mean annual concentration of nitrate was approximately the same in 1905–1906 and 1933–1934 as in the 1950s, but it has doubled since the 1950s (Fig. TB4.10.2; Turner and Rabalais 1991). The increase in total nitrogen is almost entirely due to changes in nitrate concentration (Turner and Rabalais 1991, Goolsby et al. 1999). Prior to the 1960s, nitrogen flux closely paralleled river discharge, a pattern that still holds, but the load of nitrogen per volume discharge is greater than historically.

It follows, and is supported with evidence from long-term datasets and the sedimentary record, that increases in riverine dissolved inorganic nitrogen concentration and loads are highly correlated with indicators of increased productivity in the overlying water column and subsequent worsening of oxygen stress in the bottom waters. Evidence comes from changes in diatom production, increased accumulation of diatom remains in the sediments, increased marine-sourced carbon accumulation in the sediments, decreased diversity of benthic fauna, and relative changes in benthic fauna that indicate a worsening oxygen environment (Fig. TB4.10.2; Turner and Rabalais 1994a,b; Eadie et al. 1994, Nelsen et al. 1994, Rabalais et al. 1996, Sen Gupta et al. 1996).

In addition to a steady population increase within the Mississippi basin since the mid-1800s with related inputs of nitrogen through municipal wastewater systems, human activities have changed the natural functioning of the Mississippi River system (Rabalais et al. 1999). Flood control and navigation channelisation restructured the Mississippi River's flow through the early part of the 20th century. The suspended sediment loads carried by the Mississippi River to the Gulf of Mexico decreased by one-half since the Mississippi valley was first settled by European colonists. This decrease occurred mostly since 1950, however, when the largest natural sources of sediments in the drainage basin were cut off from the Mississippi River main stem by the construction of large reservoirs on the Missouri and Arkansas Rivers (Meade 1995). This large decrease in sediments from the western tributaries was counterbalanced somewhat by a 5-to 10-fold increase in sediment loads in the Ohio River as a result of deforestation and row crop farming. Other significant alterations in landscape (deforestation, conversion of wetlands to cropland, loss of riparian zones, expansion of artificial agricultural drainage) removed most of the natural buffering capacity for removing nutrients from runoff into the Mississippi tributaries and main stem. There was an increase in the area of land artificially drained between 1900 and 1920, and another significant burst in drainage during 1945–1960 (Fig. TB4.10.2). In addition to physical re-

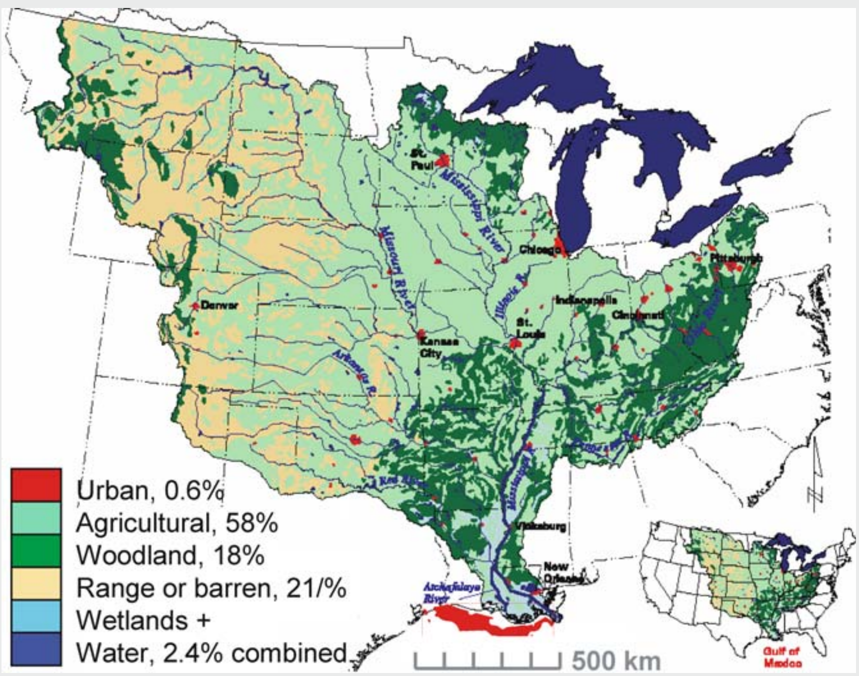


Fig. TB4.10.1. Mississippi River drainage basin and major tributaries, and general location of the 1999 midsummer hypoxic zone (Rabalais et al. 1999; from Goolsby 2000)

◀

structuring, there was a dramatic increase in nitrogen input into the Mississippi River drainage basin, primarily from fertiliser application, between the 1950s and 1980s (Fig. TB4.10.2). While the increase in drainage and fertiliser application was accompanied by an equally dramatic increase in crop production, these important alterations led to significant increases in riverine nitrate concentrations and flux to the Gulf (Turner and Rabalais 1991, Goolsby et al. 1999). The annual flux of nitrogen to the Gulf tripled between 1955–1970 and 1980–1996 to the present average of 1.6×10^6 t yr^{-1}, with 61% of that flux in the form of nitrate. Ninety percent of the nitrate inputs to the basin are from nonpoint sources, of which 74% is agricultural in origin. In addition, 56% of the nitrate enters the Mississippi River system north of the Ohio River. Organic nitrogen measurements were not regularly made before 1973, but they show no trend since then.

Evidence associates increased coastal ocean productivity and worsening oxygen depletion with changes in landscape use and nutrient management which resulted in nutrient enrichment of receiving waters. Nutrient flux to coastal systems, while essential to the overall productivity of those systems, has increased over time due to anthropogenic activities and has led to broad-scale degradation of the marine environment. The fact that the most dramatic changes in the continental shelf ecosystem adjacent to the Mississippi River have occurred since the 1950s and are coincident with an increase in nitrate load, points to that aspect of human ecology for future management scenarios.

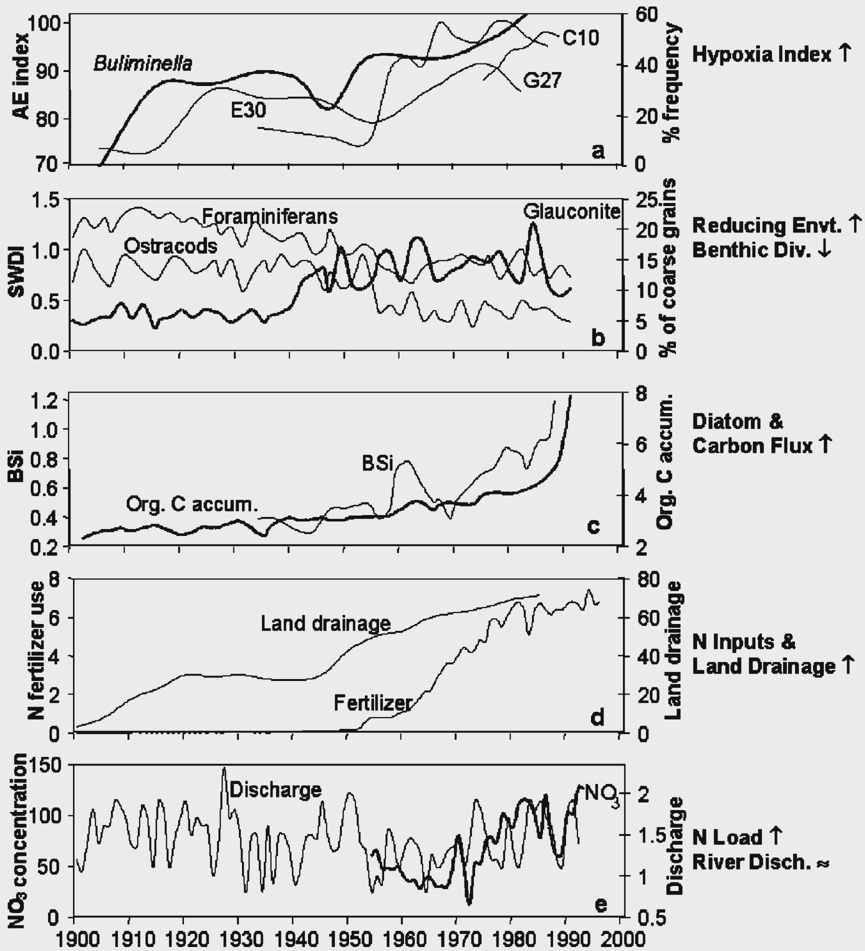


Fig. TB4.10.2. **a** A-E index for cores C10 (3-yr running average), E30, and G27 (Sen Gupta et al. 1996); percent frequency of *Buliminella* in core G27 (Rabalais et al. 1996). **b** SWDI (Shannon-Wiener Diversity Index) for foraminiferans and ostracods (Nelsen et al. 1994, TA Nelsen, National Oceanic and Atmospheric Administration, Miami, Florida, unpublished data); percent glauconite in coarse grain sediment (Nelsen et al. 1994). **c** BSi (biologically bound silica, frequency) for core E30 (Turner and Rabalais 1994b); organic carbon accumulation (mg C m^{-2} yr^{-1}) (Eadie et al. 1994). **d** Nitrogen fertiliser use in the Mississippi River basin (10^6 mt yr^{-1}) (Goolsby et al. 1999); land drainage (millions of acres) (Mitsch et al. 2001). **e** Nitrate concentration (µM) in the lower Mississippi River (Turner et al. 1998); lower Mississippi River discharge (10^4 m^3 s^{-1}) (Bratkovich et al. 1994) (from Rabalais et al. 2002)

creation of wetlands and soft defences, apart from increasing the estuarine filtering capacity for nutrients, is the creation of additional areas for carbon sequestration (Cave et al. 2003).

As far as industrial pollution is concerned, there is a residual of pollutants in the European catchments predating environmental legislation. Large-scale mining was started during Roman times (Settle and Paterson 1980) and intensified during the industrial revolution in the 19th century. Hence, many polluted sites exist in catchments across Europe, and pollutants are also stored in sediments (Salomons and Stigliani 1995). Consideration of the entire catchment becomes extremely relevant where the environmental quality of sediments in the coastal strip is affected (Text Box 4.8 above). Figure 4.15 is a sub-regional synthesis of main river catchment-coastal change issues, and provides an expert judgement-based ranking and trend analysis.

Table 4.12. Europe. Major activities, present status and trends affecting the coastal zone. (Trend: ⇒ stable, ⇑ increasing, ⇓ decreasing, sub-regions as shown in Fig. 4.14)

Anthropogenic drivers	Major state changes and impacts	Present pressure status	Trend expectations	Sub-region and main catchment basins
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/sewage)	Major	⇒/⇓ (successful point source treatment)	**North Atlantic/North Sea**
Agriculture	Eutrophication	Major/medium	⇒/⇓	a) Iberian-Biscay Plains Loire, Douro, Seine, Tejo, Guadiana, Garonne, Guadalquivir, Dordogne, Tamar
Industrialization/mining/dredging	Pollution including pollution heritage	Medium/locally major	⇓	b) Hutton-Rockall Basin Thjorsa, Olfusa, Shannon, Severn
River regulation/navigation	Erosion/flooding	Medium/locally major, e.g., Humber	⇒/⇓ (in response to predicted climate and sea level change)	c) North Sea Rhine, Elbe, Gota, Glama, Weser, Meuse, Thames, Humber
Damming/water abstraction	Reduced water flow/erosion	Minor	⇒	
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/sewage)	Medium/locally major in the south	⇒/⇑	**Baltic Sea**
Agriculture	Eutrophication	Medium/locally major	⇒	a) Southern Baltic Vistula, Odra, Nemanus, Daugava
Industrialization/mining/dredging	Pollution including pollution heritage	Medium/locally major	⇒	b) Bothnian Bay Kemijoki, Tornionjoki, Amgerman, Dalalven
River regulation/navigation	Erosion/flooding	Medium/locally major	⇒/⇓ (in response to climate and sea level change)	c) Gulf of Finland Neva, Narva, Kymijoki, Luga
Damming/water abstraction	Reduced water flow/erosion	Minor	⇒	
Industrialisation/mining/dredging	Pollution including pollution heritage	Medium/locally major (see also Sect. 4.5)	⇒/⇑ likely to increase in Russia (see also Sect. 4.5)	**Arctic**
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/sewage)	Minor/locally major (see also Sect. 4.5)	⇒/⇑ likely to increase in Russia (see also Sect. 4.5)	a) Norwegian Basin Trondheims Fjord, Soge Fjord, Alta River
River regulation/navigation	Erosion/flooding	Medium	⇒	b) Barents Sea Dvina, Pechora, Mezen, Onega
Agriculture	Eutrophication	Minor	⇒	
Water abstraction/damming	Reduced water flow/erosion	Minor	⇒	

Table 4.12. *Continued*

Anthropogenic drivers	Major state changes and impacts	Present pressure status	Trend expectations		Sub-region and main catchment basins
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/sewage)	Medium/locally major	⇒/⇑	increasing locally/temporarily (also due to tourism)	**Black Sea** a) Azov Sea Don, Kuban b) NW Black Sea Danube, Dnepr, Dnestr, Bug, Provadijska c) NE Black Sea (not considered as no major rivers)
Agriculture	Eutrophication	Medium/locally major	⇒/⇓	decreasing (in the course of recent socio-political changes)	
Industrialization/mining/dredging	Pollution including pollution heritage	Medium/locally major	⇒/⇓	decreasing (in the course of recent socio-political changes)	
Damming/water abstraction	Reduced water flow/erosion	?			
River regulation/navigation	Erosion/flooding	?			
Urbanisation (along catchments and in coastal zone)	Eutrophication (waste/sewage)	Major	⇑	(seasonal doubling due to tourism!)	**North Mediterranean Sea** a) West Aegean Sea Evros, Strymon, Axios, Aliakmon, Pinios b) North Ionian Sea Bradano, Salso, Smeto, Acheloos, Alfias c) Adriatic Sea Po, Brenta, Adige, Piave, Tagliamento, Idrija-Isonzo, Neretva, Drina, Semani, Vijose d) Tyrrhenian Basin Arno, Tevere e) Balearic Basin Rhone, Ebro, Segura, Jucar
Damming/water abstraction	Reduced water flow/erosion	Major	⇒/⇑		
Agriculture	Eutrophication	Medium/locally major, e.g., Po	⇒		
Industrialization/mining/dredging	Pollution including pollution heritage	Medium/locally major, e.g., Idrijca	⇒		
River regulation/navigation	Erosion/flooding	Medium/locally major	⇒		

4.7 Towards Coupled Coastal and River Catchment Management: DPSIR Application into Scenarios for Europe

4.7.1 Introduction

The coastal region is subject to drivers and pressures exerting their influence across global scales. Interrelated global driving pressures, such as, urbanisation, industrial development and mass tourism together with human-induced climate change, impact on regional and local resource systems with consequent local (yet generalised) management problems. Such problems require co-coordinated responses by policy makers at the national or supra-national scale (e.g., EU and beyond).

A number of general problems with implications on policy and management can be highlighted:

- the future impacts of trade and economic development, including increased dredging activities with their geomorphologic and biogeochemical impacts, the welfare consequences for natural and social systems, and the spread of invasive exotic species into local ecosystems.
- the consequences of environmental change on fisheries and the implications of more extensive and intensive aquaculture developments.
- the selection of future strategies for coastal protection and the consequences of sea defence systems (both immediately at the coast and within estuarine/fresh-water fluvial catchment areas).
- water quality deterioration, future monitoring and evaluation.
- degradation and/or destruction of a range of natural habitats and ecosystems.

Three particular characteristics of coastal zones complicate the management task: the extreme variability present in coastal systems, the highly diverse nature of such systems, and their multi-functionality and consequent high economic value. In addition, coastal areas are socio-cultural entities, with specific historical conditions and symbolic significances (Turner et al. 2001). This adds to their "value" but is also problematic because these institutional domains can have trans-national boundaries that cross national jurisdictions and require international agreements and legislation. Institutions face a problem because they are often not coincident with the spatial and temporal scales or with the susceptibility of biogeochemical and physical processes - the so-called "scaling mismatch problem" (von Bodungen and Turner 2001). The resource management task is further compounded by the existence of multiple stakeholder interests and competing resource uses and values typically of coastal zones.

4.7.2 Scenarios and Coastal Futures

The rapidly changing record of the last half century highlights the difficulties involved in forecasting future decades. The underlying context for any "futures" thinking for Europe must include an appreciation of the globalisation process and the implications of an expanding European Union and Single Market. Globalisation has brought a growing interdependence between financial markets and institutions, economies, culture, technology, politics and governance. So far, market forces and related social systems have become the increasingly dominant paradigm. In Europe, there is the additional dimension of change involving the inclusion of the countries of Central and Eastern Europe into the EU, together with their own internal transitions from centrally-planned to market-based economies and societies.

If we follow the advice of scenario analysts, then we need to foster a process by which alternative world views (eco-centrism, techno-centrism, weak sustainability or strong sustainability) and conventional wisdom are challenged and clarified, in order to focus on critical issues (Gallopin and Raskin 1998). We can envisage a future in which globalisation and liberal market conditions and values continue to evolve, or one in which coordinated and concerted collective actions are agreed upon by national governments and implemented by increasingly influential international agencies. Alternatively, self-interest and protectionism may become the dominant characteristics of a future society, with Europe gradually fragmenting rather than unifying. But even more radical change is a plausible future and the strong sustainability and "deep green" visions may also become realities.

There is no shortage of candidate scenarios to choose from and the following consideration is based on a hybrid approach that borrows from a set of scenarios previously formulated to investigate the impact of climate change, technological advances and environmental consequences in a range of contexts (Parry 2000, Lorenzoni et al. 2000, OST 1999, EEA 2000). The aim is to first provide a set of basic contextual narratives within which to set four somewhat more specific scenarios (UNEP 2002b) with relevance for coastal-catchment areas.

The narrative contexts and the scenarios are framed by two orthogonal axes, representing characteristics grouped around the concepts of societal values and forms of governance (Fig. 4.16). The values axis provides a spectrum from individualistic, self-interested, consumerist, market-based preferences through to collectivist, citizen-based communitarian preferences, often with a conservationist bias. The vertical axis spans levels of effective governance from local to global. The four quadrants are not sharply differentiated but rather are bounded by overlapping transitional zones. Change occurs as certain trends and characteristics become more

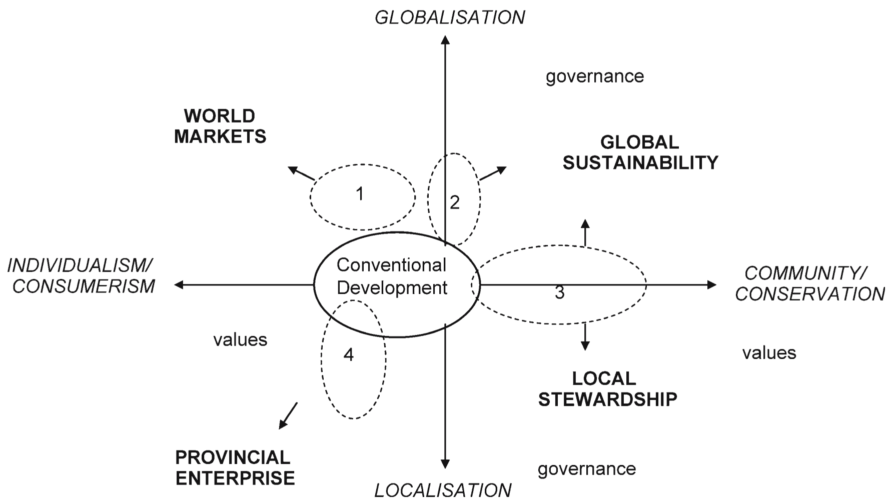


Fig. 4.16. Europe. Environmental futures scenarios

or less dominant across the different spheres of modern life – government, business, social, cultural and environmental.

Taking the four contextual background conditions first, *World Markets* is dominated by globalisation, which fosters techno-centric and often short-term societal views. Expectations about an expanding EU and Single Market are born out and economic growth remains the prime policy objective. Environmental concerns are assumed to be tackled by a combination of market-incentive measures, voluntary agreements between business and government and technological innovation. Decoupling of the growth process from environmental degradation is assumed to be feasible, not least because ecosystems are often resilient. Weak sustainability thinking is favoured and "no-regret" and "win-win" options are the only ones pushed hard by regulators. Rapid technological change, sometimes unplanned, will be the norm, as will trade and population migration. Private healthcare, information technology, biotechnology and pharmaceutical sectors of the economy, for example, will thrive, while "sunset" industries will rapidly disintegrate (e.g., heavy engineering, mining and some basic manufacturing). The internal and external boundaries of state will retreat producing a more hollowed-out structure (Jordan et al. 2000). National governments will struggle to impose macroeconomic controls as trans-national corporate power and influence escalates. Multilateral environmental agreements will prove problematic and prone to enforcement failures.

Under *Global Sustainability*, there would be a strong emphasis on international/global agreements and solutions. The process would be by and large "top down" governance. Trade and population migration would still increase but within limits often tempered by environmental considerations. EU expansion would be realised but social inequities would receive specific policy attention via technology transfer, financial compensation and debt-for-nature swaps/agri-environmental programmes.

Provincial Enterprise would be a much more heterogeneous world, EU expansion might stall and a slow process of fragmentation (economically and politically) might be fostered. A protectionist mentality would prove popular and economic growth, trade and international agreement-making prospects would all suffer.

Local Stewardship would put environmental conservation (eco-centrism) as a high priority. A very strong sustainability strategy would be seen as the only long-term option. This strategy would emphasise the need for a re-orientation of society's values and forms of governance, down to the local community scale. Decentralisation of economic and social systems would be enforced, so that over time local needs and circumstances become the prime focus for policy. Economic growth, trade, tourism (international) and population migration trends would be slowed and in some cases reversed.

4.7.3 Application of Scenarios: an Example for Europe

The use of scenario's will be illustrated for coastal futures in Europe. The four scenarios (1, 2, 3 and 4) can be broadly located in Fig. 4.16, with the arrows indicating the general direction of change over decadal time. Scenario 1 is almost a trend/baseline scenario. The policy goal of maximise GDP growth is achieved via an extended single market system stretching into central Asia. New accession states are given transitional status to ease their progress into market-based systems. The relatively weak enforcement of environmental standards in these countries fosters short-term profitability but may hinder long-term resource use efficiencies. Rapidly growing volumes of trade and travel increase the level of economic interdependence in Europe, but social cohesion remains weak, as people strive to satisfy individual consumerist preferences. Scenario 2 imposes sustainability constraints via a "top down" governance process but also encourages citizens to "think globally and act locally." Scenario 3 allows for a much more radical paradigm shift in societal values and organisations, environmental conservation and social equity rise up the political priority agenda. In Scenario 4, protectionism breeds growing disparities across the sub-regions of Europe. Inequality and possible conflicts spawn a relative isolationist response at the nation-state level. So now we turn to the implications for the future coastal zones in Europe, given the different scenarios.

Under all scenario conditions, pressures on coastal ecosystems increase, either through direct exploitation of coastal resources, including local-use changes and an increase in the built-environment at the coast; or through changes in related catchments associated with the spatial planning of development and transportation policies, changes in agriculture policy, especially trade regimes and reform of the Common Agricultural Policy (CAP). Another striking feature of the scenario analysis is that the impact of climate change does not vary significantly across scenarios until around 2030–2050 because of delays in the response of the climate system.

If *Scenario 1* conditions prevail then trade, economic development and the migration of people across Europe all increase significantly. This increase in general economic activity will outweigh improvements in energy efficiency stimulated by carbon taxes and technological change. Public transport will remain under-developed as car transport remains the dominant mode of transport. Air traffic also grows due to trade activities and international tourism. Emissions of air pollutants and greenhouse gases (GHGs) continue to rise because of the dominant effect of the energy and transport sectors of the European economies. It is also the case that effective policies to reduce CO_2 and other GHGs are slow to evolve or remain dormant. By 2030, sea-level rises (average 10 cm) will have occurred with increased flooding risks and defence costs. The extent of the built environment at the coast and across adjacent catchments expands rapidly in Western Europe but is more stable in Central and Eastern Europe if population declines continue. The number of people living in areas of increased fresh-water stress also rises as already vulnerable areas in the south of Europe face a deteriorating situation and other areas become newly stressed.

The Mediterranean coast is a particular pressure and stress problem through a combination of urban growth with inadequate wastewater treatment facilities, tourism growth and increases in intensively farmed croplands close to estuaries. While the CAP is reformed this is achieved via a stronger imposition of international market pricing regimes. Some funds are made available to provide short-run support for farmers, particularly in the new entrant countries of Central and Eastern Europe but land is still abandoned in these regions. Elsewhere land abandonment is restricted to small areas, for example, in upland areas. Overall, only the most efficient farmers survive by intensifying production and embracing genetic modification technology, with consequent diffuse pollution and other environmental risk increases.

To sum up the coastal zone consequences under *Scenario 1*, tourism impacts escalate leading to local environmental problems such as salinisation and eutrophication of coastal waters. Second homes expand in almost all areas but are particularly problematic in the Baltic and Mediterranean areas. Sea-level rise exacerbated by climate change begins to pose major difficulties and other catchment flooding events are exacerbated by the expansion of the built-environment, from the 2030s onwards. Policy responses are somewhat restricted. At the international level environmental agreements prove to be difficult to negotiate and only partially effective if and when implemented. Coastal areas are therefore by and large left in the hands of local authorities and local regulators. This forum of governance offers unpredictable results and falls well short of integrated coastal management principles and practice.

Under *Scenario 2* conditions, Europe begins to resemble more of a federal state and is characterised by strong environmental and other regulatory agencies (e.g., European Environment Agency) which promote sustainability. Transport and energy sector growth is constrained by a range of intervention policies. Internationally the World Trade Organisation adopts an environmental mandate to complement its existing remit. Nationally, green belt policies and designations, such as Natura 2000, are strengthened and ecotourism principles are supported. CAP reform is dominated by switches to funding for a range of agri-environment schemes. The more proactive "environmental" strategy succeeds in stabilising air pollution and GHGs emissions, largely because of energy-efficiency gains and extensive switching to non-fossil fuels, and declines are possible from 2030 onwards. Sea-level rise difficulties remain to be solved but policy responses are more flexible e.g., managed realignment schemes.

Areas under severe water stress remain more or less constant or fall slightly in some regions as irrigated agriculture is abandoned. Overall, Western European coasts are moved closer to integrated coastal management regimes, elsewhere basic coastal management measures are put in place and historical zoning plans revitalised. The EU Water Framework Directive (see Text Box 5.1) is fully implemented as are Regional Seas Agreements.

Under *Scenario 3*, a combination of strong framework policies designed to ensure sustainability principles can be put into practice. Most significantly, attitudinal and lifestyle changes in society generate significant falls in air pollution and GHGs emissions, beginning in the 2020s. Climate-induced sea-level rise is still a problem but is tackled almost exclusively via "soft engineering" measures and relocation schemes with compensation for sufferers. Public transport networks are encouraged and succeed in reducing the dominance of the motor car (which itself becomes significantly "cleaner" and "more efficient"). Local tourism activities flourish at the expense of international tourism and "package" holidays. The built-environment expansion is halted, except for some areas in Western Europe where development pressures remain particularly strong and a major re-conversion of lost habitats is stimulated (by more designated sites, agri-environmental schemes, managed realignment) to ensure increases in biodiversity. The total area under severe water stress is constant or declining as demands (especially from agriculture and mass tourism) are blunted by pricing policies and changing consumption patterns i.e., a decline in meat eating. Policy responses at the coast embrace integrated coastal management principles but are more effectively enabled because of the existence of voluntary partnerships across stakeholders and other participatory arrangements at the local level. This "bottom up" activity serves to complement the full imposition of the EU Water Framework Directive and Regional Seas Agreements.

Under *Scenario 4*, the expanded EU itself may fail to materialise. A fall in overall economic activity, trading activity and tourism is likely. Because of this relative economic stagnation at the micro-level (most severe in Central and Eastern Europe), overall air pollution and GHGs emissions remain stable. Sea-level rise remains a problem and there is a lack of resources to invest in both mitigation and adaptation measures. The number of people living in water stress areas increases as new areas join the vulnerable category. Less than full implementation of legislation like the EU Water Framework Directive bring forth the risk of water resource conflicts and more extensive water contamination problems. Coastal zones in Western Europe remain under built-environment/economic development, tourism, port expansion and other infrastructure growth pressures. In Central Europe, conditions are more stable but do not improve, while in Eastern Europe coastal zones could become militarised zones with restricted areas, except for port facilities.

4.8 Summary and Conclusions

Within LOICZ-Basins, a standardised framework of analysis was developed to assess the impact of land-based activities and sources on coastal systems (Kremer et al. 2002). Close to 100 catchment-coastal sea systems have been analysed and the individual assessments were scaled-up to coherent continental regions.

Large catchments, the obvious examples to be addressed within a global LOICZ synthesising effort (e.g., Nile, Yangtze, Orinoco), were part of the evaluation. However, from the perspective of coastal change, the immediate influence from land-based flows is more often generated in small to medium catchments with high levels of socio-economic activity. In smaller systems, changes in land cover and use need much shorter timeframes to translate into coastal change and may exhibit more visible impacts than in large catchments where the "buffer capacity" against land-based change is higher simply as a function of catchment size. Thus, small and medium catchments were a priority for the global LOICZ-Basins assessment. They dominate the global coastal zone (in Africa, for example, they characterise extensive parts of monsoon-driven runoff to the Indian Ocean). In island-dominated regions, such as the South Pacific or the Caribbean, frequently a whole island is a catchment affecting the islands coastal zone.

4.8.1 Catchments and Changes

The results from the continental upscaling are summarised in Table 4.13 and global trends were derived for some of the pressures and drivers; these are summarised below.

Eutrophication

The negative impacts of eutrophication are reported for all continents. In Europe and North America, nutrient run-off from agriculture is considered as the main source for excess nitrogen and phosphorus in the coastal zone. However, in South America, Africa and East Asia urbanisation (sewage) is considered a significant source. The effects of eutrophication are oxygen deficiency, harmful algal blooms, disappearing macroalgal and seagrass beds as well as potential effects on biodiversity and loss of harvestable resources. A recent compilation of global oxygen depletion (Fig. 4.17; Diaz et al. 2004) indicates a broad global incidence, but evidence from LOICZ-Basins suggests that oxygen deficiency is more widespread in South America, East Asia and Africa.

The use of mineral fertilisers in agriculture is well-documented and three periods of fertiliser nutrient consumption can be distinguished: a period of continuous rise (1950 to 1989); a period when the consumption fell (1989 to 1994), due to the decline in fertiliser use in Central Europe, the former Soviet Union and to a lesser extent in Western Europe; and a period (1994 to 2001) in which the consumption in Western Europe stabilised but increased in Asia and Latin America. Fertiliser consumption is expected to grow globally by an average 1% per year (FAO 2000b) over the next three decades (somewhat faster in developing countries than in developed). Figure 4.18 shows the values of one example year in each of these periods, respectively. However, the fastest growth rates are expected in sub-Saharan Africa where fertiliser use is currently very low, so that even fast growth rates in use will likely translate into relatively small absolute increases. The relatively slow increase after 2000 implies a

Table 4.13. LOICZ Basins. Summary tables from the regional assessments – full regional continental/sub-continental scale (ranking by expert judgment, flux and threshold data and number of sub-regions affected)

South America

Ranking	Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations
1	Urbanisation	Eutrophication	Major	⇑
2	Damming/diversion	Changed material fluxes/erosion/sedimentation	Major	⇑
3	Deforestation	Erosion/sedimentation	Medium	⇑
4	Industrialisation	Pollution	Medium	⇑
5	Agriculture	Eutrophication/pollution	Medium	⇑
6	Aquaculture	Eutrophication	Minor	⇑
7	Navigation	Erosion/sedimentation	Minor	⇒
8	Fisheries	Loss of biodiversity	Minor	⇒
9	Tourism	Erosion/eutrophication	Minor	⇑
10	Mining	Erosion/pollution	Minor	⇓

Africa

Ranking	Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations
1	Damming/diversion	Changed material fluxes/erosion/sedimentation (locally salinisation/nutrient depletion)	Major	⇑
2	Various drivers	Biodiversity loss	Major	⇑
3	Deforestation	Erosion/sedimentation	Medium	⇑
4	Agriculture	Eutrophication/pollution	Medium	⇑
5	Urbanisation	Eutrophication/pollution	Medium	⇑
6	Industrialisation	Pollution	Medium	⇑

East Asia

Ranking	Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations
1	Urbanisation/industrialisation	Eutrophication/pollution/harmful algal blooms (HABs) Water extraction	Major/ Medium	⇑
2	Damming/diversion	Changed material fluxes/coastal erosion	Major/ Medium	⇑
3	Agriculture/aquaculture	Eutrophication, pesticide pollution/diseases	Medium/ Major	⇒ ⇑
4	Deforestation	Habitat loss/modification/erosion/sedimentation/saltwater intrusion	Medium/ Major	⇓ ⇒
5	Land reclamation	Sediment budget alteration	Medium (locally major)	⇑
6	Mining (terrestrial and offshore)	Biodiversity loss	Medium/ Minor	⇒

Russian Arctic[a]

Ranking	Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations
1	Industrialisation (incl. mining/oil and gas production)	Pollution/acidification	Medium/ Major	⇒ ⇑
2	Navigation	Pollution/sedimentation	Medium/ Minor	⇑ ⇒
3	Nuclear-power, engineering, nuclear industry, navy	Radioactive pollution	Minor (locally major)	⇒
4	Urbanisation	Pollution/partly eutrophication	Minor (locally medium to major)	⇑

Table 4.13. *Continued*

Ranking	Anthropogenic drivers	Major state changes and impact	Present pressure status	Trend expectations
Russian Arctic[a] (*Continued*)				
5	Damming	Changed material fluxes/coastal erosion	Minor locally up to medium	⇒
Europe[b]				
1	Urbanisation (incl. tourism in sub-regions)	Eutrophication/pollution	Major	⇒ ⇑
2	Agriculture	Eutrophication/pollution	Medium	⇒ ⇓ (in sub-regions)
3	Industrialisation (incl. mining/dredging)	Pollution (incl. pollution heritage)	Medium	⇒ ⇓ (in sub-regions)
4	River regulation/navigation	Erosion/flooding	Medium	⇒ ⇓
5	Damming/water abstraction	Changed material fluxes/coastal erosion	Medium/minor (but major in the Mediterranean)	⇒
Caribbean				
1	Damming/diversion	Erosion/sedimentation	Major (locally)	⇑ ⇒
2	Deforestation	Sedimentation	Major	⇑
3	Tourism (land and sea-based)	Pollution/eutrophication	Major	⇑ ⇒
4	Urbanisation	Pollution/eutrophication	Major (locally)	⇑
5	Industrialisation	Pollution/eutrophication	Major (locally)	⇑
6	Agriculture	Eutrophication	Medium locally major	⇑
7	All drivers	Biodiversity loss/modification	Medium locally major	⇒ ⇑
Oceania				
1	All drivers	Biodiversity loss/modification	Major	⇑
2[c]	Mining	Pollution/sedimentation/erosion	Major (locally)	?
3	Deforestation	Sedimentation/erosion	Major	⇑
4	Urbanisation	Eutrophication/pollution/sedimentation/erosion	Major (locally)	⇒ ⇑
5	Agriculture	Eutrophication/erosion/sedimentation	Medium locally major	⇑

[a] in the Russian Arctic sub-table indicates that this ranking largely applies to the Western Russian Arctic (i.e. west of the Lena River) and that it can also be argued (to some extent) since it reflects a "broad brush" view again that neglects the partly substantial pressures deriving from drivers such as urbanization and drilling on local scales.
[b] in the European sub-table indicates that the ranking expresses a rather subjective interpolation across extremely heterogeneous sub-regions (see Fig. 4.15) where driver/pressure settings cover a broad range. For example position 5 for" Damming/water abstraction" is quite arguable since in one of the most populated sub-regions such as the Northern Mediterranean it is substantial as in other cases elsewhere such as the Vistula system. This table tries to provide the "broad brush" European Synthesis – for higher detail please refer to Fig. 4.15 and the text.
[c] in the Oceania sub-table indicates that due to the fact this area is very heterogeneous "Mining" in certain regions certainly may represent a 1 priority. However it seems to the sum of drivers/pressures that over a full regional scale the impact on the sustainability of the coastal life support ecosystems in form of biodiversity loss justifies a higher rank allocation.

Fig. 4.17. Occurrences of oxygen depletion in coastal areas (Diaz et al. 2004)

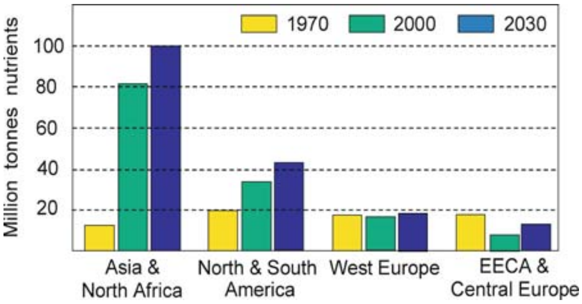


Fig. 4.18. Fertiliser consumption (1970 to 2000) and projected consumption for 2030 (IFA 2003)

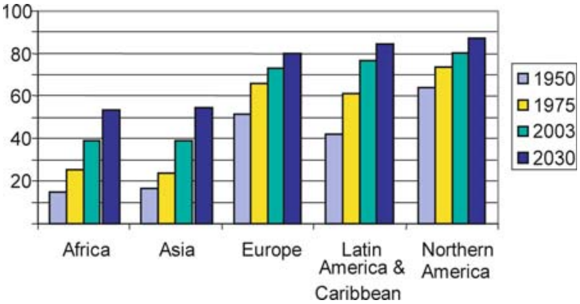


Fig. 4.19. Regional populations residing in urban areas (adapted from Urban and Rural areas 2003, United Nations Population Division 2004)

lower rate of increase of nutrient supply to the coastal zone through rivers. Hence the current situation regarding oxygen deficiency, harmful algal blooms and habitat loss may remain static and is expected not to show an improvement. Also aquaculture, an expanding coastal economic activity, will cause an additional increase of nutrient inputs into the coastal zone.

People Pressure and Urbanisation

The world urban population is growing faster than the global population as a whole. In 2003 3 billion people or 48% of humankind were living in urban settlements. The urban population is expected to increase to 5 billion by 2030; the rural population is anticipated to decline slightly from 3.3 billion in 2003 to 3.2 billion in 2030.

Following recent estimates (Small and Nicholls 2003) the coastal strip defined by a 100 km horizontal distance band and up to 100 m above sea level currently accommodates around 1.2 billion people, i.e. around 23% of the 1990 global population which translates to an average population density nearly 3 times higher than global average. Most of this near-coastal population live in relatively densely-populated rural areas and small to medium size coastal cities rather than in mega-cities. These estimates are considerably lower than earlier ones, which go up to even 60% in a comparable (see comprehensive compilation by Shi and Singh 2003). However, much more significant than absolute figures is that the continuous sprawl of coastal urbanisation is accelerating on virtually all continents at faster rates than further inland. As a consequence this demographic pressure may become increasingly more important as a source of nutrient inputs to the coastal zone reflecting for instance in the strong rise in urbanisation in Africa, Asia and Latin America (Fig. 4.19).

Erosion-Sedimentation Issues

The geomorphology of the coast is strongly affected by changes in hydrology and sediment supply. These changes are caused by the building of dams and causeways, creating reservoirs, establishing large-scale irrigation schemes and changing land use patterns. These developments change the flow of rivers and diminish the amount of sediment being carried, which, in turn, can alter coastlines. The consequence of reduced sediment can extend to long stretches of coastline where the erosive effect of waves is no longer replaced by sediment inputs from rivers. Deforestation, by contrast, can increase sediment supply and damage wetlands, submerged vegetation, deltas and coral reefs.

The LOICZ-Basins assessments contain many examples of coastal impacts from changes in hydrologic and sediment regimes at the catchment level. The commonly twinned drivers/pressures of deforestation and agriculture generally have a moderate though increasing impact at the coast. Both activities tend to result in reduced water retention in the catchment and increased soil erosion, thus increasing both the severity of flooding and the amount of sediment carried as river bedload and in suspension. The problem is acute in the small to medium-sized African catchments.

Diversions and damming of waterways are seriously affecting the erosion-accretion equilibrium of large stretches of the South American coastline. These effects are most apparent where water resources are scarce, or where there is rapid population growth in coastal metropolitan areas, or where arid climates prevail. Examples can be found along the north-eastern Brazilian coast and the Caribbean coasts of Colombia and Venezuela.

In many estuaries, changing river sediment load alters the sedimentation-erosion equilibrium within the estuary or delta. Recognising that coarse-grained bedload normally represents 10% or less of the total sediment discharge delivered to the coastal zone, we assumed that a decrease of 5% of the total sediment flux represented a critical threshold, beyond which the coastal system is likely to show evidence of significant deterioration (coastal erosion). In South America, this level of change results in mangrove siltation in estuaries of north-eastern Brazil, in severe erosion of mangroves in south-eastern Brazil, and in sandy beach erosion on the coasts of Buenos Aires Province in Argentina and in north-eastern Brazil. Damming and water abstraction in the Indus River have led to major changes in the morphology of the Indus delta (see Text Box 4.11).

The drivers and pressures causing a changing sediment flux to the coast are manifold but, reservoirs and irrigation channels can retain a large proportion of the fluvial sediment discharge (Syvitski 2003, Syvitski et al. 2005). According to Vörösmarty et al. (1997, 2003), 663 dams with large reservoirs (greater than 0.5 km^3 maximum storage capacity) store about 5 000 km^3 of water, or approximately 15% of the global river water discharge. These large reservoirs intercept more than 40% of global water discharge with 25 to 30% (4–5 Gt yr^{-1}) of the sediment flux being trapped behind dams.

> **Text Box 4.11. Change in the morphology of the Indus delta resulting from damming and water abstraction in the Indus River system**
>
> *Peter R. Burbridge*
>
> Entrapment of sediments in the river course and water abstraction can lead to subsidence of deltas, with consequent loss of biodiversity and fisheries. One example is the Indus delta, where major water impoundments have resulted in a decrease in water flow and the delivery of mineral sediments and organic matter to the delta. With the reduction in the annual supply of these materials, the subsidence of the sediments forming the delta is no longer offset by their replenishment. With greatly restricted river flow, the functions of the estuary are reduced and both primary and secondary production has fallen. With subsidence, the biodiversity of mangroves has decreased and with it, the shrimp fishery has declined.

4.8.2 Information Gaps

Issues of Scale

LOICZ-Basins has shown that humans play a powerful role in altering hydrology and material fluxes and fate and transformation in the coastal realm (Meybeck 2003, 2004c, Salomons 2004, Syvitski et al. 2003, 2005, Vermaat et al. 2005). This influence has greatly changed in rate and scale through the past two centuries, but a thorough understanding of the causal linkages between these drivers/pressures and the coastal state changes at multiple scales remains a major challenge.

Global Scale Science

The common nature of the many drivers/pressures globally, such as intensification of agriculture, expansion of construction and infrastructure in the coastal zone and effects of impoundments, requires greater analysis (Meybeck 2004c). Coastal signals are frequently masked by a complex interplay of land-based processes, e.g., the effects of increased erosion due to land-use and cover change being concealed by the enormous trapping efficiency of worldwide damming activities. In addition, climate change affects the hydrology of catchments and land use in catchments with direct implications for erosion, sediment supply and nutrient loads. It is expected that low-lying areas, such as deltas and large estuaries, will be particularly sensitive to changes in sediment supply. A global assessment focusing on past and future changes in coastal morphology in response to the multitude of changes in catchments is needed.

A major challenge is measuring and understanding the temporal interplay between changes at the catchment level and their (often delayed) impact at the coast. The issue of delayed and non-linear responses has been described for pollutants. Stored chemicals/pollutants from past pollution events (e.g., mining, industry, intensive agriculture) may take several years before they reach the coast due to the buffering capacity of soils and sediments (Salomons and Stigliani 1995). However, while the phenomenon of temporal delay in sediment supply and its effect on coastal morphology and ecosystems has been identified, it has not yet been sufficiently addressed at the global scale.

Regional Scale Science

Supporting the findings of the LOICZ global investigation on estuarine metabolism (see Chap. 3), LOICZ-Basins consolidated the view that science must look beyond the confines of a coastal area ascribed by narrow shoreline boundaries and take a "source-to-sink" approach when considering the coastal zone. Management of coastal systems to ensure the continuity of coastal goods and services for human society in the context of river catchment-coastal sea interaction needs to be addressed at predominantly regional scales.

The EuroCat study showed that the use of socio-economic scenarios to couple models can be helpful. One of its major outcomes was a clear demonstration that wetland creation (e.g., restoring former coastal features) provided major benefits, including restoration of habitats, recreational areas, enhanced environmental services (i.e., denitrification and trapping of phosphorus) and sequestering of carbon. In addition, calculations for the Humber (UK) catchment showed that coastal realignment is more effective than hard engineering structures in defense against sea-level rise. These single measure approaches at local and sub-regional scales provide effective resolution to a number coastal issues (e.g., nutrient reduction, sustainability by maintenance of environmental goods and services in the coastal zone, impacts of sea-level and CO_2 rises). Importantly, the studies demonstrated benefits based on economic data as well as on ecological grounds. Elsewhere in the world, the need for habitat restoration has generally been argued mostly on ecological principles.

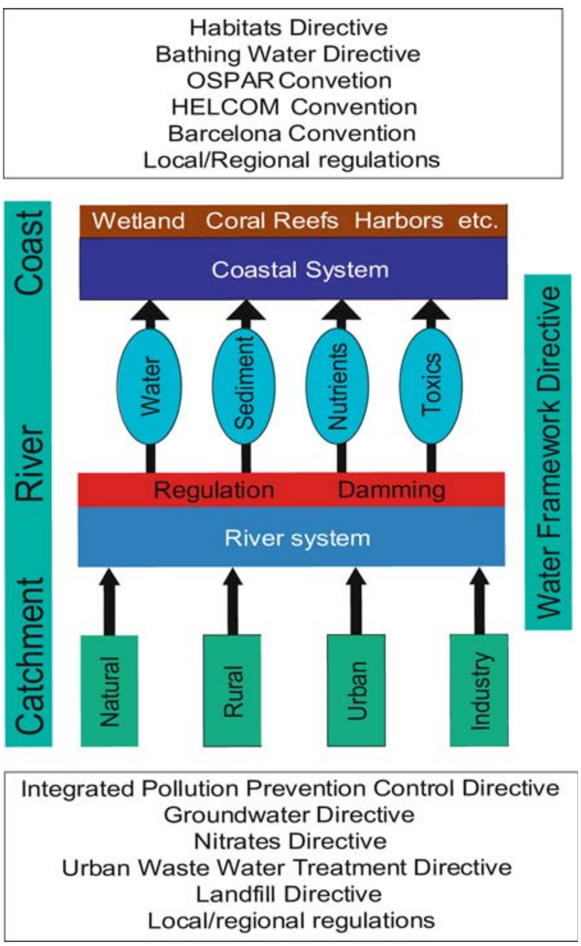


Fig. 4.20. Europe. Mismatch between regulation in catchments and in the coastal region (based on Ledoux and Turner 2003)

Integration of Policy and Management with the Catchment-Coastal Continuum

Effective management and sustainable use of the coastal zone requires not only detailed integrated scientific assessment of the catchment-coast continuum, but an analysis and understanding of the policy framework for the region. Generally, as with the science, there is a lack of integration between policies for the catchment and those for the coastal region. In Europe, for instance, there is not a lack of policies and directives (Fig. 4.20), rather the policies refer either to the catchment or to the coastal region; they are not integrated across the catchment-coast continuum that constitutes the coastal zone. However, the recent European Union Water Framework Directive provides an enlightened and more holistic approach, which should make the integrated scientific results from projects such as EuroCat more accessible and amenable for management and for policy applications.

The success in meeting all these challenges will continue to be constrained by the paucity of data and information, and disciplinary and interdisciplinary capacity in particular in the socio-economic fields. In principle, the quantification of the findings, prediction and risk/vulnerability analysis at the catchment basin scale and at full regional and global scales, remain major challenges for the future LOICZ.

References

Arthurton RS, Kremer HH, Odada E, SalomonsW, Marshall Crossland JI (eds) (2002) African Basins: LOICZ global change assessment and synthesis of river catchment–coastal sea interaction and human dimensions. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 25

Behrendt H, Kornmilch H, Opitz D, Schmoll O, Scholz G (2002) Estimation of the nutrient inputs into river systems – experiences from German rivers. In: Kremer H (ed) (2002) Regimes of Regional and Global Coastal Change. Special Issue, Reg Environ Change 3:107–117

Bratkovich A, Dinnel SP, Goolsby DA (1994) Variability and prediction of freshwater and nitrate fluxes for the Louisiana-Texas shelf: Mississippi and Atchafalaya River source functions. Estuaries 17:766–778

Cadee N, Dronkers J, Heip C, Martin J-M, Nolan C (1994) ELOISE. European Land-Ocean Interaction Studies science plan. EUR 15608, European Commission, Luxembourg

Cave R, Brouwer R, Coombes E, Hadley D, Turner K, Lorenzoni I (2003) Futures scenarios and cost effectiveness analysis of alternative policy options to improve water quality in the Humber catchment in the United Kingdom. EuroCat Report

Chen JT (1994) Study on the environmental protection countermeasures of Pearl River coast zones. In: Wong CK, Chu KH, Chen QC, Ma XL (eds) Environmental research in the Pearl River and coastal area. Guangdong Higher Education Press, Guangzhou, pp 153–161

Chen C-TA (2000) The Three Gorges dam: reducing the upwelling and thus productivity in the East China Sea. Geophysical Research Letters 27:381–383

Chen C-TA, Liu JT, Tsuang B-J (2004) Island-based catchment – The Taiwan example. Reg Environ Change 4:39–48

Cole, J.J. and N. F. Caraco. In Press. Primary production and its regulation in the tidal-freshwater Hudson River. In: Levinton J, Waldman J (eds). The Hudson River Ecosystem

Diaz RJ, Nestlerode J, Diaz ML (2004) A global perspective on the effects of eutrophication and hypoxia on aquatic biota. In: Rupp GL, White MD (eds) Proceedings of the 7th international symposium on fish physiology, toxicology and water quality, Tallinn, Estonia, May 12–15, 2003, pp 1–33. EPA 600/R-04/049, US Environmental Protection Agency, Ecosystems Research Division, Athens, Georgia

Eadie BJ, McKee BA, Lansing MB, Robbins JA, Metz S, Trefry JH (1994) Records of nutrient-enhanced coastal productivity in sediments from the Louisiana continental shelf. Estuaries 17:754–765

EEA (2000) Cloudy crystal balls: an assessment of recent European and global scenario studies and models. Environmental Issues, European Environmental Agency, Series No17, Copenhagen

EEA (2003) Europe's environment: the third assessment. Environmental Assessment, European Environmental Agency, Report No. 10, Copenhagen

FAO (2000a) Fertilizer requirements in 2015 and 2030. FAO, Rome, Italy

FAO (2000b) FAOSTAT database collections, Food and Agriculture Organization of the United Nations (FAO), Rome (*http://www.apps.fao.org*)

Fekete BM, Vörösmarty CJ, Grabs W (1999) Global, composite runoff fields based on observed river discharge and simulated water balances. World Meteorological Organization-Global Runoff Data Center, Report 22, Koblenz, Germany

Gallopin GC, Raskin P (1998) Windows on the future: global scenarios and sustainability. Environment 40(3):7–11, 26–31

Gandrass J, Salomons W (2001) PORII. Dredged material in the Port of Rotterdam– Interface between Rhine catchment area and North Sea. GKSS Research Center Report

GESAMP (2001). A sea of troubles. GESAMP (IMO/FAO/UNESCO/IOC/WMO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Reports and Studies. FAO, Rome, No. 70 and No. 71

Goolsby DA (2000) Mississippi Basin nitrogen flux believed to cause Gulf hypoxia, EOS Transactions of the American Geophysical Union 81:325–327

Goolsby DA, Battaglin WA, Lawrence GB, Artz RS, Aulenbach BT, Hooper RP (1999) Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin: topic 3 report for the integrated assessment of hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series. NOAA Coastal Ocean Program, Silver Spring, MD, No. 17Humphrey S, Burbridge P, Blatch C (2000) US lessons for coastal management in the European Union. Marine Policy 24:275–286

Gordeev VV, Andreeva E, Lisitzin AP, Kremer HH, Salomons W, Marshall Crossland JI (2005): Russian Arctic Basins: LOICZ Global Change Assessment and Synthesis of River Catchment–Coastal Sea Interaction and Human Dimensions. A desk study of the Russian Arctic. LOICZ Reports & Studies No. 29, ii+xxx pages, LOICZ, Texel, The Netherlands

Green P, Vörösmarty C, Meybeck M (in press) Global distribution of river nitrogen fluxes in pristine and impacted basins. Biogeochem

Griffiths F, Young OR (1990) Protecting the Arctic's environment: impressions of the co-chairs. Working Group on Arctic International Relations, Reports and Papers 1990-1, Hanover, New Hampshire

Hetling LJ, Stoddard A, Brosnan TM, Hammerman DA, Norris TM (2003) Effect of water quality management efforts on wastewater loadings over the past century. Water Environ Res 75:30

Hong GH, Kremer HH, Pacyna J, Chen C-TA, Behrendt H, Salomons W, Marshall Crossland JI (eds)(2002) East Asia basins: LOICZ global change assessment and synthesis of river catchment–coastal sea interaction and human dimensions. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 26

Howarth RW, Jaworski N, Swaney DP, Townsend A, Billen G (2000a). Some approaches for assessing human influences on fluxes of nitrogen and organic carbon to estuaries, In: Hobbie JE (ed) Estuarine Science. A synthetic approach to research and practice. Island Press, Washington DC

Howarth RW, Swaney DP, Butler TJ, Marino RM (2000b) Climatic control on eutrophication of the Hudson River estuary. Ecosystems. 3:210–215

Jordan AJ, Lorenzoni I, O'Riordan T, Turner RK (2000) Europe in the new millennium. In: Parry, ML (ed) Assessment of the potential effects of climate change in Europe: The Europe ACACIA Project. University of East Anglia, Norwich, pp 35–45

Kellogg JN, Mohriak WU (2001) The tectonic and geological environment of coastal South America. In: Seeliger U, Kjerfve B (eds) Coastal marine ecosystems of Latin America, Springer-Verlag, Berlin, pp 1–16

Kjerfve B, Wiebe WJ, Kremer HH, Salomons W, Marshall Crossland JI (eds) (2002) Caribbean basins: LOICZ global change assessment and synthesis of river catchment/island–coastal sea interaction and human dimensions. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 27 (part)

Kremer HH, Salomons W, Crossland CJ (2002) Human dimensions of land-based fluxes to the coastal zone: the LOICZ-Basins approach. In: de Lacerda LD, Kremer HH, Kjerfve B, Salomons W, Marshall Crossland JI, Crossland CJ (eds) South American basins: LOICZ global change assessment and synthesis of river catchment–coastal sea interaction and human dimensions. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 21, pp 61–72

Lacerda De LD, Kremer HH, Kjerfve B, Salomons W, Marshall Crossland JI, Crossland CJ (eds) (2002) South American basins: LOICZ global change assessment and synthesis of river catchment-coastal sea interaction and human dimensions. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 21

Ledoux L, Turner RK. (2003), Report on the Institutions, stakeholders and potential/actual conflicts of interest and value within a given catchment, *EUROCAT WD, 33. http://www.cs.iia.cnr.it/EUROCAT/project.htm*

Lorenzoni I, Jordan A, Hulme M, Turner RK, O'Riordan T (2000) A coevolutionary approach to climate change impact assessment: Part I. Integrating socio-economic and climate change scenarios. Global Environmental Change – Human policy dimensions 10:57–68

Meade RH (ed) (1995) Contaminants in the Mississippi River, 1987–1992. US Geological Survey Circular 1133, US Dept of the Interior, US Geological Survey, Denver, Colorado

Meybeck M, Laroche L, Durr HH, Syvitski JPM (2003) Global variability of daily total suspended solids and their fluxes in rivers. Global and Planetary Change 39:65–93

Meybeck M, Dürr H, Vogler J, Lacharte L, Gueguen Y (2004a) Space analysis of catchment/coast relationships. Synthesis report: European catchments, catchment changes and their impact on the coast, "EuroCat", European Commission, DG Research, 5th Framework Programme, Contribution No. EVK1-CT-2000-00044

Meybeck M, Vogler J, Moatar F, Durr H, Laroche L, Lachartre L (2004b) Analysis of temporal variability in river systems. Synthesis report: European catchments, catchment changes and their impact on the coast, "EuroCat", European Commission, DG Research, 5th Framework Programme, Contribution No. EVK1-CT-2000-00044

Meybeck M, Vogler J, Turner K, Hisschemöller M, van Tilburg, M (2004c). River-coast integration in European regional seas. Part I: Improving basin-coast integration (Meybeck and Vogler). Part II: Scenario analysis (Turner). Part III: Institutional analysis (Hisschemöller and van Tilburg). Synthesis report: European catchments, catchment changes and their impact on the coast, "EuroCat", European Commission, DG Research, 5th Framework Programme, Contribution No. EVK1-CT-2000-00044

Mills EL, Scheuerell MD, Carlton JT, Strayer DL (1997) Biological invasions in the Hudson River basin: an inventory and historical analysis. New York State Museum Circular 57

Mitsch WJ, Day JR, Gilliam JW, Groffman PM, Hey DL, Randall GW, Wang N (2001) Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River basin: strategies to counter a persistent ecological problem. BioScience 15:373–388

Morcom N, Harvey N, Marshall Crossland JI (2002) Oceania basins. LOICZ global change assessment and synthesis of river catchment–coastal sea interaction and human dimensions. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 27 (part)

Nelsen TA, Blackwelder P, Hood T, McKee B, Romer N, Alvarez-Zarikian C, Metz S (1994) Time-based correlation of biogenic, lithogenic and authigenic sediment components with anthropogenic inputs in the Gulf of Mexico NECOP study area. Estuaries 17:873–885

Nixon SW (2003) Replacing the Nile: are anthropogenic nutrients providing the fertility once brought to the Mediterranean by a great river? Ambio 32(1):30–39

OST (1999) Environmental futures. Report for the UK National Technology Foresight Programme. Office of Science & Technology, DTI/Pub 4015/IK 399 NP, VRN 99647, London, UK

Parry M (ed) (2000) Assessment of potential effects and adaptations for climate change in Europe The Europe Acacia Project, Jackson Institute, University of East Anglia, Norwich

Rabalais, NN, Turner RE, Justic D, Dortch Q, Wiseman WJ Jr. (1999) Characterization of hypoxia: topic 1 report for the integrated assessment of hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 15. NOAA Coastal Ocean Program, Silver Spring, MD, 167 pp

Rabalais NN, Turner RE, Justic D, Dortch Q, Wiseman WJ, Sen Gupta BK (1996) Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries19:386–407

Rabalais NN, Turner RE, Justic D, Dortch Q, Wiseman WJ (1999) Characterization of hypoxia: topic 1 report for the integrated assessment of hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series. NOAA Coastal Ocean Program, Silver Spring MD, No. 15

Rabalais NN, Turner RE, Scavia D (2002) Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. BioScience 52:129–142

Salomons W (2004) European catchments: catchment changes and their impact on the coast. Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

Salomons W, Stigliani WM (1995) Biogeodynamics of pollutants in soils and sediments. Springer, Berlin

Salomons W, Turner RK, de Lacerda LD, Ramachandran S (eds) (1999) Perspectives on integrated coastal zone management. Springer-Verlag, Berlin, Heidelberg

Sen Gupta BK, Turner RE, Rabalais NN (1996) Seasonal oxygen depletion in continental-shelf waters of Louisiana: historical record of benthic foraminifers. Geology 24:227–230

Settle DM, Patterson CC (1980) Lead in Albacore: guide to lead pollution. American Science 207:1167–1176

Shi H, Singh A (2003) Status and inter-connections of selected environmental issues in the global coastal zones. Ambio 32:145–152

Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. Journal of Coastal Research 19, 3:584–599

Smith SV, Dupra V, Marshall Crossland JI, Crossland CJ (2000) Estuarine systems of the South American region: carbon, nitrogen and phosphorus fluxes. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 15

Smith SV, Swaney DP, Talaue-McManus L, Bartley JD, Sandhei PT, McLaughlin CJ, Dupra VC, Crossland CJ, Buddemeier RW, Maxwell BA, Wulff F (2003) Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. BioScience 53: 235–245

Swaney, D.P., D. Sherman, and R. W. Howarth. 1996. Modeling water, sediment, and organic carbon discharges in the Hudson-Mohawk Basin: coupling to terrestrial sources. Estuaries. 19:833–847

Syvitski JMP (ed) (2003) Supply and flux of sediment along hydrological pathways: anthropogenic influences at the global scale. Global and Planetary Change, Special Issue 39:1–199

Syvitski JPM, Vörösmarty C, Kettner AJ, Green P (2005) Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308:376–380

Thomas H, Bozec Y, Elkalay K, de Baar HJW (2004) Enhanced open ocean storage of CO_2 from shelf sea pumping. Science 304: 1005–1008

Turner RE, Rabalais NN (1991) Changes in Mississippi River water quality this century. Implications for coastal food webs. BioScience 41:140–148

Turner RE, Rabalais NN (1994a) Coastal eutrophication near the Mississippi River delta. Nature 368:619–621

Turner RE, Rabalais NN (1994b) Changes in the Mississippi River nutrient supply and offshore silicate-based phytoplankton community responses. In Dyer KR, Orth RJ (eds) Changes in fluxes in estuaries: implications from science to management. Proceedings of ECSA22/ERF Symposium, International Symposium Series, Olsen & Olsen, Fredensborg, Denmark, pp 147–150

Turner RE, Qureshi N, Rabalais NN, Dortch Q, Justic D, Shaw RF, Cope J (1998a) Fluctuating silicate:nitrate ratios and coastal plankton food webs. Proceedings of the National Academy of Science, USA 95:13048–13051

Turner RK, Adger WN, Lorenzoni I (1998b) Towards integrated modelling and analysis in coastal zones: principles and practices. LOICZ Reports and Studies. LOICZ, Texel, The Netherlands, No. 11

Turner RK, Bateman IJ, Adger WN (eds) (2001) Economics of coastal and water resources: valuing environmental functions. IT Week, Kluwer, Dordrecht

UNEP (2002a) Africa environment outlook – past, present and future perspectives. Earthprint Limited, Stevenage, England

UNEP (2002b) Integrating environment and development, 1992–2002. UNEP, Nairobi

UNPD (2004) Urban and rural areas, 2003. United Nations Population Division *http://www.un.org/esa/population/publications/wup2003/2003urban_rural.htm*

Vermaat JE, Ledoux LC, Salomons W, Turner RK (eds) (2005) Managing European coasts; past, present and future. Springer, Berlin, Heidelberg, New York

Von Bodungen B, Turner RK (eds) (2001) Science and integrated coastal management. Report of the 85th Dahlem Workshop Berlin December 12–17 1999. Dahlem University Press, Berlin

Vörösmarty CJ, Sharma KP, Fekete BM, Copeland AH, Holden J, Marble J, Lough JA (1997) The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26: 210–219

Vörösmarty CJ, Fekete BM, Meybeck M, Lammers RB (2000a) The global system of rivers: its role in organizing continental land mass and defining land-to-ocean linkages. Global Biogeochemical Cycles 14(2):599–621

Vörösmarty CJ, Fekete BM, Meybeck M, Lammers RB (2000b) Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution. Journal of Hydrology 237:17–39

Vörösmarty C, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM (2003) Anthropogenic sediment retention: Major global-scale impact from the population of registered impoundments. Global and Planetary Change 39(1/2):169–190

Wall, GR., Riva-Murray, K, Phillips, PJ (1998) Water Quality in the Hudson River Basin, New York and Adjacent States, 1992–95. U.S. Geological Survey circular 1165.

Wong CKC, Leung CKM, Poon BHT, Lan CY, Wong MH (2002) Organochlorine hydrocarbons in human breast milk collected in Hong Kong and Guangzhou. Arch Environ Contam Toxicol 43:364–372

Wong AMW, Wong MH (2004) Recent socio-economic changes in relation to environmental quality of the Pearl River delta. In: Kremer H (ed) (2004) River catchment-coastal sea interaction and human dimensions. Reg Environ Change 4:28–38

World Commission on Dams (2000) Dams and development – a new framework for decision-making. The report of the World Commission on Dams, Earthscan Publications Ltd, London and Sterling VA

Yu Z, Zhang J, Yao Q, Mi T (1999) Nutrients in the Bohai Sea. In: Hong GH, Zhang J, Chung CS (eds) Biogeochemical processes in the Bohai and Yellow Sea, Dongjin Publication Association, Seoul, pp 11–20

Chapter 5

Synthesis of Main Findings and Conclusions

Peter Burbridge, Robert W. Buddemeier, Martin Le Tissier and Robert Costanza
Contributor: *Laurie Ledoux*

5.1 Global Change and Sustainable Use of Earth's Coastal Zones

It is clear that global change to the environment is having a major influence on the functioning of coastal systems and their ability to sustain human development. A key outcome of the first 10 years of LOICZ is that, although major river systems have a profound influence on coastal and nearshore marine systems at a regional level, the mounting pressures from human development and their effects on coastal systems are felt most acutely at small to medium individual catchment scales. Furthermore, it is becoming increasingly evident from the LOICZ studies that the cumulative effects of human-induced changes in small- to medium-scale river systems may well be greater than those attributed to major river systems.

The LOICZ research described in the preceding chapters has demonstrated the importance of biogeochemical fluxes, nutrients and sediments from river catchments in the coastal zone for the availability of living and non-living resources for human society. The outcomes from LOICZ research have demonstrated that investigation of changes to coastal systems cannot be confined within administrative boundaries. Instead, studies need to be oriented towards watershed- and catchment-based perspectives to study coastal dynamics and to integrate the results with management of human activities. This reinforces the emerging concepts of integrated coastal management where the "coastal zone" is treated as part of a dynamic continuum linking terrestrial and marine components, rather than as an isolated "zone" that can be managed without reference to natural and human-induced changes to hydrology, or fluxes of materials in upland and oceanic systems.

The river basins or catchments (LOICZ-Basins) studies have helped to integrate the human dimensions[2] to global environmental change by identifying the major social and economic drivers that lead to pressures with a direct or indirect influence on the state of ecosystems and corresponding impacts on biological, chemical, geophysical, social and economic conditions. These studies demonstrated common as well as unique features concerning the rate and scale of change in human pressures among the different bio-climatic regions.

Integration of natural and social science dimensions in the LOICZ programme has clarified the principal problems and issues associated with global environmental change and consequent sustainability of human uses of coastal systems, including:

- eutrophication;
- pollution;
- changing erosion/sedimentation equilibrium;
- mounting impoverishment in the biodiversity of estuarine waters and coastal seas through a reduction in river-borne nutrients and organic matter;
- loss of ecosystem goods and services that help to sustain food security, economic development and improvements in social welfare; and
- increasing vulnerability of human societies to natural coastal hazards affecting settlements, public and private investment, property and lives.

Given the pivotal role that coastal areas and resources play in sustaining the social and economic welfare of up to 50% of Earth's population, the major challenge that humans face today is to recognise and manage the consequences of adverse impacts from both natural and human-induced changes to coastal systems. History has shown how difficult it is to motivate nations to work together in addressing these issues at a global scale. However, much can be achieved at regional, nation-state and local levels to sustain human use of coastal systems. This can be done through initiating improvements in the management of human activities within catchments as well as within the marine and terrestrial components of the "coastal zone." LOICZ methodologies have allowed up-scaling of local information to a global scale that can

---

2 For the purposes here, a definition of human dimensions is "*the effects of human activity on large physical and biological systems, the impacts of environmental change on people and societies, the responses of social systems to actual or anticipated environmental change, and the interactions among all these processes*" (US NRC Committee on the Human Dimensions of Global Change).

then be down-scaled and applied to other local areas where there is a paucity of information. A major benefit from the LOICZ thematic studies is the provision of scientific evidence that could strengthen information available for policy, planning and management initiatives at small to medium to large scales. At the same time, LOICZ studies have greatly enhanced our understanding of the responses of coastal systems at a global scale.

5.2 Progress in Meeting IGBP-LOICZ Goals

During the past 10 years, the scientific effort of the LOICZ project has been directed towards answering the generic question:

How will changes in land use, sea level and climate alter coastal ecosystems, and what are the wider consequences?

The broad goals of LOICZ in addressing this question have been:

1. Determination at global and regional scales:
   a fluxes of materials between land, sea and atmosphere through the coastal zone;
   b capacity of coastal systems to transform and store particulate and dissolved matter;
   c effect of changes in external forcing conditions on the structure and functioning of coastal ecosystems.
2. Determination of how changes in land use, climate, sea level and human activities alter the fluxes and retention of particulate matter in the coastal zone and affect coastal morphodynamics.
3. Determination of how changes in coastal systems, including responses to varying terrestrial and oceanic inputs of organic matter and nutrients, will affect the global carbon cycle and the trace gas composition of the atmosphere.
4. Assessment of how responses of coastal systems to global change will affect the habitation and usage by humans of coastal environments, and to develop further the scientific and socio-economic bases for the integrated management of coastal environments.

These goals and objectives have been addressed by a global network of scientists in which the active and collaborative participation of scientists from developed and developing countries has been vital to the successful conduct of the research and dissemination of results of the LOICZ programme. This network has compiled many local case studies, which form the data and information base that has been up-scaled for construction of the global synthesis.

Progress has been made in generating a comprehensive overview of the changes in Earth system processes affecting the coastal zone, the role of coastal systems in global change and the current state of coastal metabolism. This includes identifying simple proxies in the form of demographic and hydrological parameters, that can support the prediction of the state of coastal systems. Typology approaches supported by analytical and visualisation software have been developed to assist in the interpolation of these results for remote areas where primary information is lacking, thus enabling a first order up-scaling to a global synthesis.

Important scientific questions have been answered. For example, estimates of carbon fluxes and their modification by natural systems and human activities in coastal regions have been developed through the up-scaling of local nutrient budget data collated and analysed by LOICZ. Another success is the identification and analyses of nutrient loads transmitted to coast systems and an evaluation of the global increase in nutrients over recent decades. The LOICZ research has also provided new insights into the influence of global climate change on the dynamics of coastal systems with respect to sediments, groundwater and sea-level and how these may influence the long-term habitation of coastal areas and sustainable use of natural resources.

The main findings from the thematic studies produced new information of value in broadening our understanding of global systems and addressing management challenges at various scales, centring upon three areas of investigation:

1. The Material Fluxes effort relied more heavily on scientific evaluation of fluxes, measurements and models. Although most of the results stemmed from paper studies and scientific workshops, new data were assembled through the publication of compilations of information and model results and a series of field measurements and experiments. The latter activity was a joint LOICZ/SCOR working group on submarine groundwater discharge. The results of the overall effort consist primarily of an enhanced understanding of the issues involved in coastal zone fluxes, of the variety of forcing functions controlling them, and in the development of an inventory of relevant tools and the understanding of where and how they may best be applied.
2. The Biogeochemical Budget effort pursued a course that was in many ways intermediate between, and conceptually linking, the other two – using local expertise to assess the nature and status of biogeochemical fluxes in coastal waters in a quantitative, inter-comparable fashion. The systematic classification of budgets and associated flux data, and the terrestrial and marine systems they represent, provided a basis for identifying potential functional similarities among measured and similar unstudied systems – the typological up-scaling approach.
3. The River Basins effort used a standardised approach to identify and assemble regional "expert judgment"

assessments of the characteristics and conditions of drainage basins and their known or perceived relationship to the conditions of the associated estuarine or coastal waters. These assessments, based on a mixture of quantitative measures and qualitative judgments, were codified in terms of ranked variables that have the potential to be formulated in at least semi-quantitative fashion, and related to typological definitions and known mechanisms of change.

Each of these thematic areas was underpinned by the use of the Driver-Pressure-State-Impact-Response (DPSIR) framework in socio-economic evaluations (Turner et al. 1998) and was enhanced through model developments and application in regional sites (e.g., Southeast Asia) where terrestrial socio-economic models were linked with coastal ecosystem (biogeochemical) models (Talaue-McManus et al. 2001). Awareness of this method of assessing local and regional global changes and management was transferred to other parts of the world through collaborative involvement of LOICZ scientists with international capacity building initiatives by Intergovernmental Organisations (IGOs). Companion work (Wilson et al.2004) revised and extended the values for the world's ecosystem goods and services, earlier estimated by Costanza et al. (1997).

These efforts were not only individually productive, but complementary and convergent in both methods and results. A final, more rigorously integrative evaluation of coastal zone functions in the global context remains the major challenge for the second phase of LOICZ (*http://www.loicz.org*). The results and relationships summarized in this chapter lay out the new framework and starting point.

5.3 Key Findings

LOICZ research has substantiated, and enhanced our understanding of, the critical importance of four principal issues concerning the sustainable human use of coastal areas and their ecological systems.

1. The coastal domain is the most dynamic part of the global ecosystem and the realm most subject to natural and anthropogenically-induced global change. The obvious trends over the last century, of increasing human population in the coastal lands and the allied pressures on coastal systems, will undoubtedly serve as a powerful catalyst for direct changes in the coastal zone and more broadly for Earth's systems.
2. At a global scale, coastal systems play a significant role in regulating global change. The concentration of population and inadequate planning and management of economic activities in coastal areas have a major influence on the health and productivity of all Earth's coastal systems. At a regional and local scale, there are specific actions that can be taken within the coastal realm to ameliorate anthropogenic influences on atmospheric, marine and terrestrial systems. However, there are limits to what can be achieved at a global scale through adjustments to policy, investment and management of human activities within coastal zones.
3. Coastal change cannot be studied or managed in isolation from river systems. Anthropogenic impacts on hydrological systems, sediment and materials fluxes and energy transfers within river basins have a far greater influence on coastal areas and on the resilience and stability of coastal systems than is commonly understood. It is therefore critically important to couple the management of human activities within river basin systems and management of human activities within coastal areas in order to:
   a avoid irreversible loss of the dynamic equilibrium that allows coastal systems to function and continue to help regulate global carbon cycles, material fluxes and energy budgets;
   b maintain the flows of renewable resources and environmental services that help to sustain human societies;
   c meet international standards of environmental conduct, such as control of marine pollution and conservation of biological diversity; and
   d reduce the rate of increase in vulnerability of human societies located within coastal regions to natural and human-induced hazards.
4. Although large river systems such as the Amazon and the Mississippi generate the major input of freshwater, energy and materials into the coastal and marine environment, it is the small- to medium-sized river basin systems that are more sensitive to human-induced and climatic influences on hydrology and material fluxes. For instance, the same town on a large river system/catchment has far less impact than on a small river system because of temporal and spatial scales as well as buffering capacity. The buffering capacity of large versus small systems is reflected in the time between change and when a response is found/observed, and in the magnitude of the response. A large system will show a slow response to land clearing, with a small increase in turbidity, whereas a small catchment will show a fast response and much higher increases in turbidity because downstream impacts of changing land use and changes in hydrology are much greater. In comparison to the large river systems, much less is known about these smaller rivers – how they are changing, the response of associated coastal systems and their role in global change.

5.3.1 The Coastal Domain

The Earth's coastal regions form the interface between the marine and terrestrial realms and are the focus of human-induced and natural global change. Physical, biological and chemical processes drive land–ocean interactions that result in a series of unique coastal habitats adapted to strong terrestrial and/or marine forcings. Human societies have developed a strong dependence on the natural resources and products available from these ecosystems.

Coastal processes and natural ecosystems are subject to changes which vary greatly in geographic scale, timing and duration and lead to very dynamic and biologically productive coastal systems that are vulnerable to additional pressures resulting from human activities. The sustainability of human economic and social development is vulnerable to natural and human-induced hazards as a result of our poor understanding of the dynamics of land-ocean interactions, coastal processes and the influence of poorly planned and managed human interventions.

There is mounting concern about the sustainability of human use of the coastal zone from degradation in ecosystems and habitats reducing the availability of resources and amenities. The LOICZ project developed new insights into how human dimensions and natural systems interact and are intimately combined in the various pressures on, and resultant state of, the coastal domain. However, it is apparent that existing tools and concepts for measurement and analyses are inadequate to meet the needs for understanding human–nature interactions. There is heterogeneity in the expression of pressures, changes and state of coastal systems and that limited comprehensive data and information are readily available and/or accessible at all scales of measurement. In particular, societal demands on the scientific community for information and knowledge to resolve management issues are increasing despite the relatively poor history of communication between science and users (Biesecker 1996, Kremer and Pirrone 2000). In such cases, participatory approaches in programme design, implementation and assessment can prove fruitful (Crossland 2000). Frequently asked questions relate to sustainability issues (e.g., How do we identify wise-use options?), planning and management approaches (e.g., How can we measure and predict impacts and changes?) and policy-related developments (e.g., What are the risks and vulnerability to change?). Answers to such questions are critical to the sustainable improvement of human economic and social conditions. Over the past decade, there have been major advances in our scientific understanding of the chemical, physical and biological processes that maintain the health, productivity and functions of coastal ecosystems that are vital in providing socio-economic goods and services for humankind. Methods and concepts for integrating information across disciplines also continue to be developed.

While our scientific knowledge of coastal zone processes has improved, there remain major challenges for assessing the impact of regional and global change across multiple temporal and spatial scales on the functioning of coastal ecosystems. At the local level these interacting challenges are fourfold:

- Identify, model and analyse *global changes* that affect a local coastal system, such as natural variability, climate change and associated changes in the hydrological cycle, and those due to changes in global economy/trade and policy.
- Identify, model and analyse *regional (trans-boundary and supra-national) changes* that are primarily the result of regional and national drivers and pressures in the coastal zone,
- Model and assess *regional changes* at the level of river catchments (e.g., damming, land use change) that affect the downstream coastal zone.
- Map existing *stakeholders interests and differences* in the perception of coastal values at regional scales – differences that need adaptation of management options to local social conditions, beliefs and attitudes.

Sustainable management and its supporting research have to take these interacting changes into account and this requires a holistic approach. In this holistic approach the coastal region is part of the catchment–coast continuum and part of a regional socio-economic framework, which is embedded in a global setting. Many studies have dealt with isolated aspects of this continuum and framework, while a few integrated studies have dealt with either coastal zone management or river catchment management. The various studies show significant differences in spatial and temporal scales.

The hydrological system that links atmospheric, terrestrial and ocean processes forms the fundamental organising framework for developing our understanding of such complex relationships and changes. The LOICZ programme has therefore given major emphasis to the use of river basins as a functional unit for examining both natural and human-induced changes and their effects on terrestrial, coastal and ocean systems.

5.3.2 River Basins: Assessment of Human-induced Land-based Drivers and Pressures

LOICZ adapted and used the Driver-Pressure-State-Impact-Response (DPSIR) framework to illustrate the dominant pressures and effects on the global coastal realm.

The drivers and pressures on coastal systems that we observe and measure are now predominantly the result of societal function and human behaviour and may be amenable to management and policy decisions (response) in specific situations. In the first instance, small to medium-sized and relatively undeveloped catchments may offer a greater opportunity to modify policies, infrastructure investment and land-use and resources management as intervention will probably be less constrained by cross-boundary issues than would highly developed catchments of major river systems. Further, it is increasingly apparent that the forcing on coastal ecosystems by most natural drivers and pressures is being greatly modified in both extent and intensity by human activities. The characteristics of the LOICZ-Basins studies can be summarised as:

1. Predominantly founded on qualitative data and information gathered through a series of regional workshops, which developed "expert" typologies wherein quantitative thresholds associated with Driver-Pressure-Response parameters have been estimated.
2. Confirming the importance of human-induced changes to land cover, hydrology and material fluxes compared with the effects of cyclic climatic and tectonic events.
3. Creating a mechanism for an overview of human-induced changes in river catchments and their effect on coastal systems.
4. Showing that scale issues related to institutional and biogeochemical parameters are highly variable at both local and regional levels.
5. Having current management practices which are strongly focussed on only water resources issues that hinder the adoption of more integrated management approaches based on consideration of water in a wider goods and services context. Such a strategy would integrate hydrological and material fluxes into policy, investment and resources management strategies and plans, and institutional structures.
6. In a data-rich situation, it is possible to demonstrate that participatory approaches to the integration of science and management can enrich problem definition and the development of pragmatic and effective management of coastal systems use based on the continuum from catchment through to coastal ocean systems. Scenario development is a primary tool to foster such integration.
7. Having identifiable trends and factors that influence progressive change. One example is the periodic flushing of agricultural chemicals into an estuary resulting from major storms. This creates a change in the nutrient fluxes over time and will influence biological production in the estuary and adjacent coastal waters. While such events can be monitored in a discrete time frame, the period over which land management practices or agricultural policies will change to mitigate such events will extend over a far longer time-scale.

An example of the relevance of these findings to the policy arena can be seen in consideration of the European Union's Water Framework Directive (Text Box 5.1).

Where change impacts coastal systems that do not have an inherent inertia to the change imposed upon them from changes in the catchment basin, change cannot be studied or managed in isolation, because it is caused by human activities that are predominantly land-based. Examples include damming that reduces the supply of sediment resulting in major changes in the stability of coastal systems, such as a coastline shifting from an accretionary to an erosional state. Changing land use, for example deforestation, can increase erosion and sediment delivery as agricultural soils are more prone to erosion compared with forested ones. Changing land use can also increase the supply of nutrients, with some time-delay due to the buffering effect of soils after the land-use change occurs. The nature of land-based activities and their impact on the coastal zone may go through a cycle that reflects the industrial landscape and regulatory efforts (Fig. 5.1).

The DPSIR framework adopted by LOICZ has been successfully used in scoping and ranking pressures and drivers within river basins across continents. The overall trend of the drivers affecting coastal seas indicates an accelerated catchment-based influence on coastal zones and their functioning within the Earth's system. Although pressures and drivers are similar between basins, notable differences exist at the large-scale regional level with regard to ranking as well as future trends. Damming is considered an over-riding issue on the African continent; it is also an important issue in other countries, but less so than eutrophication. The main causes of increased

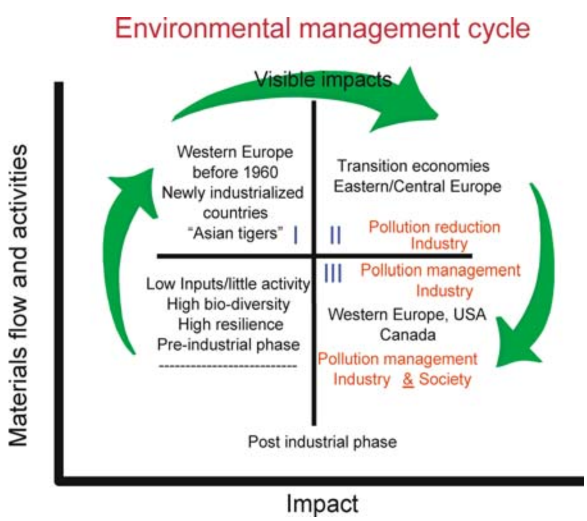


Fig. 5.1. Linkages between governance, economic development and global change in the coastal zone (from Salomons et al. 1995)

Text Box 5.1. An example of policy response at catchment scale: the European Union Water Framework Directive

Laure Ledoux

Given the generally large fluxes of nutrients and contaminants from catchments, any policy response seeking to improve coastal water quality should target activities at the catchment scale. One example of such integrated catchment-coastal zone management policy is the recent European Union Water Framework Directive (WFD), adopted in June 2000. The new directive integrates previously existing water legislation, updates existing directives according to new scientific knowledge and strengthens existing legal obligations to ensure better compliance (Kaika and Page 2002). Earlier legislation on water had gone through two distinct phases (Kallis and Butler 2001, Kaika and Page 2002). The first one (1975–1987) was primarily concerned with public health and setting standards for water quality for different uses (drinking, fishing, shellfish and bathing). In the second phase (1988–1996), priorities shifted towards pollution control, in particular for urban wastewater and agricultural runoff, with an effort to set emission limit values for different pollutants in water bodies. The third phase, which saw the birth of the WFD, came after a state of the environment report showed that these policies had been effective in terms of reducing point-source pollution, but that diffuse pollution remained a major problem (EEA 1998, Kaika and Page 2002). The new Directive is an attempt at more integrated and sustainable water management, expanding the scope of water protection for the first time to all waters, from surface water to groundwater, and from freshwater ecosystems to estuaries and coastal waters. It encapsulates the new directions in European environmental policy institutionalised in the Maastricht Treaty in 1992 and further reinforced by the Amsterdam Treaty in 1997. The Member States agreed to the objective of sustainable development as a Community policy, to the Community responsibility for environmental policy within the limits of subsidiarity, and to the integration of environmental policy into other community policies. More specifically the precautionary principle, the principle of prevention of pollution at source and the polluter-pays principle were all adopted (Barth and Fawell 2001).

Kallis and Butler (2001) point out that the directive introduces both new goals and new means of achieving them (i.e., new organisational framework and new measures). The overall goal is a "good" and non-deteriorating "status" for all waters (surface, underground and coastal). This includes a "good" ecological and chemical quality status for surface water. Ecological status involves criteria for assessment divided into biological, hydro-morphological and supporting physico-elements for rivers, lakes, transitional and "heavily modified" water bodies. For groundwater, the goal is a "good status" defined in terms of chemical and quantitative properties. A principle of "no direct discharges" to groundwater is also established, with some exemptions (e.g., mining). In addition, "protected zones", including areas currently protected by European legislation such as the Habitats Directive, should also be established, with higher quality objectives.

Organisationally, measures to achieve the new goals will be co-ordinated at the level of river basin districts, i.e., hydrological units and not political boundaries. Authorities should set up River Basin Management Plans, to be reviewed every six years, based on identifying river basin characteristics, assessing pressures and impacts on water bodies and drawing on an economic analysis of water uses within the catchment. Monitoring is also an essential component, determining the necessity for additional measures. Finally, an important innovation of the Directive is to widen participation in water policy-making: river basin management plans should involve extensive consultation and public access to information.

Following the DPSIR terminology, the main "response" element of the WFD is the program of measures (Fig. TB5.1.1). "Basic" measures should be incorporated in every river basin management plan, at a minimum including those required to implement other EU legislation for the protection of water. If this doesn't suffice to achieve good water status additional measures should be introduced following a "combined approach", which brings together the two existing strategies of Environmental Quality Standards (EQS – the legal upper limits of pollutant concentrations in water bodies) and Emission Limit Values (ELV – the upper limits of pollutant emissions into the environment). ELVs are applied first, through the introduction of best available technology for point source pollution, or best environmental practice for diffuse pollution. If this is not enough to reach EQSs, more stringent ELVs must then be applied in an iterative process. Furthermore, Member States should follow the principle of full cost recovery of water services, ensuring that water pricing policies are in place to "provide adequate incentives" for efficient use of water.

Although some aspects of the WFD are specifically adapted to the European situation, some key principles could usefully be considered as a template for other areas of the world. In particular, the principles of ecosystem-based water policy, cost-recovery, administrative management at the scale of river basins and stakeholder participation are all elements of integrated water management that could usefully be considered elsewhere. However, the information and scientific knowledge required within the Directive are very significant, already posing major challenges to scientists in the European Union (Ledoux and Burgess 2002, Murray et al. 2002). Furthermore, administrative and institutional reforms needed for successful implementation of the Directive will involve significant costs in many European countries (Kallis and Butler 2001). This might be a significant barrier towards implementation in less-developed countries where administrative, institutional and information-gathering costs could be even higher. Humphrey et al. (2000) also note that although the new directive provides an integrated approach to river basins associated to coastal waters, any sustainable coastal management policy would need to take a wider geographical perspective, as physical, ecological and socio-economic influences of and on the cost go further than the narrow strip considered. The new EU communication on Integrated Coastal Zone Management: a Strategy for Europe (COM/00/547 of 17 Sept. 2000) is a step towards a more comprehensive coastal zone management policy.

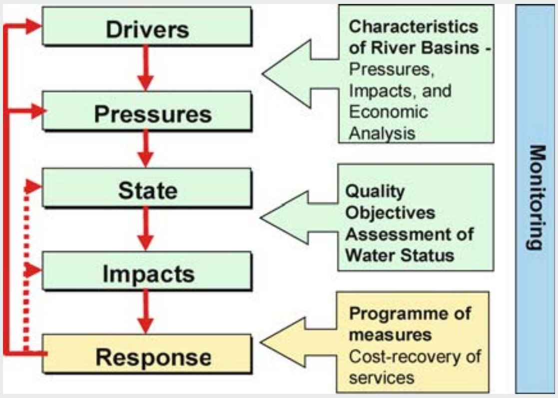


Fig. TB5.1.1. DPSIR framework and WFD tasks

inputs of nutrients are urbanisation and agriculture in South America and Asia. However, in Europe where effective sewage treatment is widespread, agriculture is the main cause of coastal eutrophication. In certain areas of Europe, regulatory efforts have decreased phosphorus release and this decrease has caused, or is expected to cause, a change in the ecosystem, affecting fisheries yields negatively. Thus, the success of regulatory efforts has caused environmental changes that were not anticipated by the general public or the fisheries sector.

In terms of major pressures on the coast, contaminants and industrialisation received in most cases a low ranking, with the exception of the Russian Arctic where large-scale nuclear industries have caused an input of radionuclides into rivers and the Arctic seas.

The global inventory of pressures on the coastal system has clearly shown that many of the drivers are outside the influence/jurisdiction of the local coastal manager; in particular, the economic activities within catchments that have a pronounced influence on the coast. The regulatory frameworks the coastal manager has to implement are rarely related to the regulatory frameworks that exist at the catchment level. The "airshed" also needs to be taken into account as atmospheric deposition is a more important input of nutrients and pollutants than in the past and crosses different boundaries than does the watershed. There is clearly a mismatch between these regulations and the scientific approach, which considers the catchment and the coast as a continuum.

Other examples of pressures outside the realm of the coastal manager's responsibility include those related to transport (shipping), for example, the introduction of exotic species and the use of toxic chemicals for antifouling on ships. Regulatory measures in these cases have to be taken at the global level.

Clearly outside the sphere of influence of the local manager are the effects of global change, such as sea-level rise and increased frequency of storm events. In addition, global change affects the catchments through alteration of the hydrological regime, migration of population and changing patterns in global trade, which in turn affect the nature of economic activities in the coastal zone and in the catchment.

5.3.3 Material Fluxes

The dynamic processes acting on coastal zones are impacted by human influences acting on upland water resources and changing the timing, flux, and dispersal of water, sediments and nutrients. These influences include:

- Changes in the timing of when water is transported to the coast by reservoirs constructed for electrical power generation and flood mitigation, or entire water diversion schemes.
- Changes in the amount of water transported to the coast due to water use for urban development, industry and agriculture.
- Regional decreases in the delivery of sediment to some coasts resulting from trapping within reservoirs, barrages and other water and erosion control structures.
- Regional increases in the delivery of sediment to some coasts resulting from increased soil erosion associated with agriculture, construction (urban development, roadways), mining and forestry operations.
- Changes to the flux rates and loading of nutrients to the coast (e.g., from storing of carbon in sediments of reservoirs, elevated nitrogen fluxes from agricultural activities).

The consequences of these human impacts on the Earth's coastal zones are:

- loss of ecosystem health and diversity;
- reduced vitality of coastal wetlands, mangroves, seagrass beds and reefs;
- reduced production of renewable resources, including environmental services;
- impacts on coastal stability, biostability and shoreline modification;
- changed residence time of contaminants and changed sediment grain size; and
- changes to the dispersal area and plume intensity of particulate loads from rivers.

5.3.3.1 *Impacts of Local, Regional and Global Sea-level Fluctuations*

The last decade has seen an increase in the accuracy of global sea-level measurement with new techniques (e.g., satellite altimetry and geodetic levelling). The historic record of sea-level change interpreted from tide-gauge data shows that the average rate of sea-level rise was greater in the 20th century than in the 19th century. The raw tide gauge data need to be corrected for local and regional influences either with modelling calculations or directly by geological investigations near tide-gauge sites. The estimated mean sea-level rise based on tide-gauge records for the 20th century have been in the range of 1–2 mm yr^{-1} with a central median value of 1.5 mm yr^{-1}.

Current scientific projections of sea-level rise are within a range of 0.09 to 0.88 m for the period 1990 to 2100 with a central value of 0.48 m. The projections could vary by as much as –0.21 to +0.11 m if current rates of terrestrial storage of sediments continue. Irrespective of the local variability resulting from the interaction of sediment supply and coastal erosion processes, achievement of an average sea-level rise of 0.48 m by 2100 would require a greatly accelerated rate (2.2 to 4.4 times) in sea-level rise compared to that of the 20th century.

There is still a need for better information on local and regional sea-level change and more accurate prediction of their impacts. An important element of sea-level change research is the need to improve prediction of impacts on different types of coast, such as rocky coasts, sandy coasts, deltaic coasts, tropical coasts and low latitude coasts. Many of these are already eroding (e.g., sandy coasts), but new threats are appearing in areas such as the Arctic coast, where changes in the extent of sea-ice have in places produced a different wave climate and consequent coastal impacts.

It is equally important to place present and predicted sea-level changes into their geological context in order to provide a perspective on the cyclical nature of sea level and the extent to which present and predicted changes are perturbations from natural cycles, particularly the 100 000 year glacial/interglacial cycles. The geological record also shows that there has been a globally variable but predictable coastal response to the sea-level rise following the last glacial maximum. In addition, recent geological research shows prospects of linking geologically recent records of the last 2 000 years with sea-surface temperatures and regional climate change.

Our ability to assess the scale and rate of change to coastal systems associated with relative sea-level rise is limited, and there is a need to refine and upscale regional vulnerability assessments. Improvement to our ability to conduct such assessments will enhance decision-making concerning an appropriate combination of the three options for intervention: retreat, accommodate or protect.

5.3.3.2 *Sediment Flux to the Coast*

The sediment load delivered by the Earth's rivers has a major influence on the dynamics of coastal change. Ocean energy (tides, waves, currents) reworks river-supplied coastal sediment to form and maintain our varied coastlines: estuaries, beaches and deltas. If the sediment supply from the land is reduced, then ocean energy will begin to relentlessly attack and erode shores, driving the coastline inland.

Climatic shifts are often the major factor driving sediment flux. Large continents are influenced by a number of climatic phenomena operating over different time periods. Individual regions may respond quite differently to climate forcing, which will depend on the duration of the climate fluctuation and the variability in spatial properties of such parameters as relief, geology and hydrological processes. As one example, an increase in the frequency and intensity of El Niño events will increase the supply of sediment to local coastal areas at a sub-global scale – in different hemispheres and different continents.

Human activities have substantially increased the continental flux of sediment during the last two millennia from changes in:

- land-use practices that have increased soil erosion (e.g., agriculture, deforestation, industrialisation, mining),
- practices that have decreased soil erosion, including engineering of waterways, and
- the trapping and retention of sediment by reservoirs and rivers.

Most of the sediment eroded off the land remains stored between the uplands and the sea. Retention of sediment in large reservoirs constructed during the last 50 years has decreased the global flux of sediment to the coastal zone by 30%. This is likely to be exacerbated by the increased development of small impoundments at the farm scale, as management responses for erosion control and matter storage (Smith et al. 2001). Because lower sediment loads are reaching the coast, shoreline erosion is accelerated and coastal ecosystems deteriorate with a corresponding change (including reduction) in local fisheries yields. The coupling of increased nutrient inputs and decreased sediment loads (e.g., the Nile which is now nutrient-enriched due to fertilisers and wastewater although sediment loads are reduced because of the Aswam dam) may promote coastal-zone eutrophication and hypoxia.

5.3.3.3 *Dynamics at the Estuarine Interface*

The amount of sediment in motion and the length of time it is retained in coastal systems such as estuaries and deltas is unknown. Geomorphic processes are the most important single factor controlling the residence time for sediments in the coastal zone. The interactions between geomorphology and advective processes are non-linear, making the prediction of the fate of sediment input into coastal areas difficult, across both short and long time-periods.

In many countries in the wet tropics intense rainfall, coupled with deforestation, land clearing, overgrazing and other poor farming practices, has considerably increased soil erosion and sediment flux. For tropical estuaries and coastal seas, environmental degradation due to increased sedimentation and reduced water clarity is a serious problem.

In contrast, developed countries in mid-latitudes have estuaries that are generally suffering from sediment starvation due to extensive damming and river-flow regulation. Sediment retention by dams leads to accelerated coastal recession (e.g., deltas of the Colorado, Nile, Ebro, Mississippi and Volta rivers; Text Box 4.10), as will soon be the case for the Yangtze River in China. Water diversion schemes also accelerate coastal erosion.

5.3.3.4 *Groundwater Inputs*

Subterranean and sub-seafloor fluid flows in the coastal zone have a significant influence on sediment and nutrient fluxes, and can be a source of biogeochemically important constituents including nitrogen, carbon and radionuclides. If derived from land, such fluids provide a pathway for new material fluxes to the coastal zone and may result in diffuse pollution in regions where groundwater is contaminated.

5.3.3.5 *Management Implications*

Greater attention should be given to the contribution of human activities and natural processes acting on catchments and the resulting fluxes of energy, water and sediment reaching coasts. Reduction of sediment inputs to coastal systems combined with relative sea-level rise will increase the vulnerability of coastal areas, together with associated human activities and corresponding private and public investment, to natural hazards such as flooding, storm over-wash, erosion and salinisation of surface and ground waters. In many humid regions, increased intensity and periodicity of surface water flows and rates of soil erosion can lead to accelerating risks of riverine flooding, rapid accretion of coastlines and degradation of coastal systems through siltation. Human-induced changes to material and energy fluxes will also have an adverse influence on primary and secondary biological production and the ability of coastal ecosystems to sustain demands for renewable natural resources.

Given the high rates of sediment retention associated with the damming of rivers and flood control structures and the corresponding negative effects on coastal systems, thought should be given to the managed release of trapped sediments to help achieve a better balance between erosion and accretion processes within estuarine-nearshore coastal systems. Conversely, increased soil conservation and reduction of sediment loads in humid regions may help to reduce the negative effects of increased siltation rates.

A distinction should be made between natural coastal vulnerability and vulnerability of human lives and property that may be at risk from the effects of climate change, changes in the sedimentary budgets of coastal systems and sea-level rise. In many cases, poor coastal planning results in the need for rapid and expensive adjustment to the consequences of sea-level change. However, there is a need for a better understanding of local sea-level change, in addition to adopting a precautionary approach, in planning for the consequences of the predicted global sea-level rise.

Greater attention should also focus on groundwater inputs to coastal systems. Groundwaters typically have higher concentrations of dissolved solids than most terrestrial surface waters. Submarine groundwater discharge (SGD) often makes a disproportionately large contribution to the flux of dissolved constituents, including nutrients and pollutants. In addition, discharging groundwater interacts with and influences the recirculation of seawater, which can affect coastal water quality and nutrient supplies to nearshore benthic habitats, coastal wetlands and breeding and nesting grounds. One of the more important implications for coastal zone managers is nutrient (or other solute) loading to nearshore waters. Amelioration of impacts in the coastal zone from these inputs could be the basis for improved land-use planning and may place limits on development.

Managers should have increased awareness of the relative relationships and priorities of SGD among the multiple factors considered in coastal management activities. This requires modifications in the current approaches for studying groundwater discharge so that:

- The scale of emphasis becomes that of management areas – probably tens to hundreds of kilometres. Currently, scientists are typically performing investigations at the lower end of this scale (although some tracer investigations work at scales of 10–100 km).
- Scientists may study one area for years, often reflecting the typical 2–3 year grant cycle. Managers, on the other hand, will have need for relatively simple and rapid diagnostic and assessment tools to evaluate local importance and management issues related to SGD in specific settings. The concerns could be either natural processes or human activities.

5.3.4 Biogeochemical Budgets

The LOICZ biogeochemical budgeting effort updated the estimates of dissolved inorganic nutrient (N, P) loading to the ocean, including revised estimates for geographic distribution of that loading and the load response to human population and runoff. These estimates are substantially higher than those of Meybeck (1982) and somewhat elevated above the estimates by Meybeck and Ragu (1997), as shown in Chap. 3. Also, the new estimates contain values for inorganic nutrient load to the ocean under "pristine" or pre-human impact conditions. While direct updates of dissolved organic nutrients or particulate nutrients are not provided, the following general observations can be made:

- globally, inorganic nutrient loads seem likely to have changed the most; this is consistent with earlier estimates by Meybeck and others; and
- although it might be expected that greatly elevated erosion would have increased particulate nutrient delivery to the ocean (based on analyses of the USA; Smith et al. 2001), this seems not to be the case for particulate material in general. Apparently most particulate erosion products have been retained in river channels and impoundments.

It can be argued that the changed inorganic nutrient loading has little impact at a continental shelf scale.

This is based on the loading for the ocean as a whole, where cycling between the deep ocean and surface ocean (for both N and P) and between the surface ocean and the atmosphere (for N) are far larger than can be accounted for by the nutrient load from land. This suggests that, apart from some small but significant fraction of these internal cycling exchanges between the continental margin and the open shelves, the terrestrial load generally is probably not significant at the scale of the continental shelves, excepting some specific examples, such as Mississippi River and adjacent continental shelf.

This does not imply that the terrestrial load is not important or that shelf cycling is not important in the global ocean nutrient cycles. Rather, the argument is that the importance of the shelf is largely felt at a local scale, especially in bays, estuaries and inner shelves. These small-scale features are the "first line of defence" against the delivery of products to the ocean – under both pristine and Anthropocene conditions. Particulate materials tend to sediment near the sites of their delivery to the ocean, and reactive dissolved inorganic materials tend to react there. Some dissolved nutrients, however, may be taken up and regenerated several times close to the source or at much greater distances following dispersal by currents. The strong negative log-log relationships seen between the absolute rates of the non-conservative fluxes and either system size or system exchange time argue that the most rapid rates of net material processing occur inshore. Integration of either the "raw" non-conservative fluxes of ΔDIP and ΔDIN or the derived fluxes of $[p-r]$ and [nfix – denit] suggests that these rapid, small-system inshore fluxes dominate global shelf fluxes i.e., size matters. Internal cycling exchanges within estuaries and nearshore marine areas are thus very important with respect to river basin and coastal zone management.

The scale of analysis used in the LOICZ biogeochemical approach confirms our previous understanding of the coastal zone as a source or sink of CO_2 (see Smith and Hollibaugh 1993). More organic matter is delivered to the ocean than is buried there. About half of the organic matter delivered to the ocean is particulate, and most of that apparently sediments near the point of delivery. Some dissolved organic matter apparently reacts with particles and probably also settles in the nearshore region. Other dissolved organic matter does not have this fate; it is apparently decomposed via a combination of photo-oxidation and microbial processes. More than half of the organic matter delivery is oxidized somewhere in the ocean, with about 7×10^{12} mol yr^{-1} of net oxidation in the coastal zone and 16×10^{12} mol yr^{-1} in the open ocean.

There are, however, two aspects of this analysis of carbon flux that bear elaboration. In the first place, comparison of estimated coastal and open ocean net primary production estimates of 500×10^{12} and $3\,000 \times 10^{12}$ mol yr^{-1}, respectively, indicates that the coastal ocean is substantially more heterotrophic (production/respiration ratio = 0.97) than the open ocean ($p/r = 0.998$). In the second place, the apparently slight net heterotrophy of the global ocean ($p/r = 0.994$; $[p-r] = -23 \times 10^{12}$ mol yr^{-1}) is an important part of understanding oceanic function and linkage to the slightly autotrophic land. However, this net heterotrophy is quantitatively insignificant in the oceanic role as a sink for anthropogenically generated CO_2. That sink strength is about 10 times the source strength of net oceanic heterotrophy and is (globally, on the 150-year time scale over which humans have significantly perturbed this flux) dominated by atmospheric partial pressure and the physical chemistry of seawater. Clearly, on longer time-scales the so-called biological pump and continental shelf pump are influenced by biogeochemical processes in both the open ocean and the coastal ocean.

5.4 Now and into the Future

The inter-relationships among the thematic studies described above can be simplified as follows:

- Material fluxes of water and sediment are the vectors for the nutrients and carbon, and the controls on the exchange times determine the nature and products of the biogeochemical "reactors" formed by estuaries and coastal systems.
- These fluxes are controlled by the natural features of landscape and climate, but are substantially modified by human activities – the focus of the LOICZ-Basins effort.
- Ultimately, more accurate quantification and up-scaling of coastal biogeochemical processes, as well as prediction or management of possible changes both regionally and globally, will involve merging the disparate understandings of the fluxes and their natural and socio-economic controls.
- The coastal budget systems are the natural common focus of these efforts, as shown by initial successes in describing nutrient loads to the coastal zone as functions of runoff and population and by the difficulty of predicting the effects of these loads on coastal systems, both in specific regions and globally.

An illustrative example of integrative linkages between components of LOICZ research is the coupling of land-ocean interactions between specific types of terrestrial basins and coastal configurations. An observation emerging from the biogeochemical budget studies, supported by findings from the material flux studies, is that there are qualitative differences between the functioning of large and small coastal systems and, similarly, between the large and small drainage basins that discharge their fluxes to the reactive inner-shelf zone of the coast. Large-basin fluxes, although quantitatively dominant on a cumulative global scale, directly influence only a minor part of the length of the world coastline.

In addition, there is a similar socio-economic/human dimension dichotomy between the large and small basins. Coastlines that have catchments that are compact enough for social and economic interaction between the nearshore and the more inland inhabitants (so that the entire unit is likely to be contained within the same national or sub-national political or administrative jurisdiction), present qualitatively different needs and opportunities for coastal zone management compared to those where the coast and the hinterland are socio-economically or politically decoupled. Since the former arguably account for more of the coastline, it is important that the visibility of the larger basins is not allowed to divert attention from the quantitative coastal importance of the distinctive smaller catchments.

Another conceptually integrative factor is the issue of coastal exposure and complexity. In Fig. 5.2, red boxes indicate some of the regions where river basins (large or small) discharge into waters that are protected from direct or rapid exchange with the open ocean by barrier islands or deep, complex estuaries and embayments. These environments strongly condition the fluxes of water and sediment in the marine environment that are reflected in the exchange, or residence, time – shown above to be one of the important characteristics of the coastal biogeochemical "reactor" system.

5.4.1 River Basin Factors

New institutional arrangements will be required for the coastal zone to foster inter-sectoral cooperation, coordination and eventual integration of policy, investment, plans and management arrangements to make full use of the results of the emerging scientific knowledge. These can help to improve the sustainability of use of coastal areas and resources while avoiding increased vulnerability in such uses to natural hazards. Development of participatory partnerships between the natural and social sciences and the users of scientific knowledge will be critical to future progress from both a scientific and a management standpoint. Consideration of drivers and pressures requires exploration of the differences in perceptions held by various groups of stakeholders. Often cultural differences lead to separate perceptions of coastal values and hence the "acceptable" or "consensus" management options will require a regional-historical perspective.

The impact of local civil strife and warfare on the coastal system is often insufficiently addressed or unknown. Examples where impacts have been observed are in the Arabian Gulf (after the first Gulf war) and in Nigeria, both cases involving major oil pollution. Delay times between changes and the impact of drivers and pressures, and the potential for a non-linear response of the coastal system (e.g., geomorphologic change, ecosystem change) are recognised, but quantitative information to allow predictive modelling is lacking.

5.4.2 Material Fluxes

A major finding of the LOICZ research is that the influence of humans and/or climate affects smaller river basins more dramatically than larger river basins, due to the modulating capacity of large rivers. Therefore, new techniques must be developed to address the coastal response in these sensitive smaller systems. Scaling techniques must also be employed to address the quality and usefulness of our global databases, since:

1. most of the observational data was determined across only a few years (and intra-annual variability can exceed inter-annual variability by an order-of-magnitude), and
2. observational data sets are already a few decades old during a time of rapid change resulting from human impact. Information on groundwater is a case in point.

Additional data collection describing groundwater dynamics is required in many areas, especially in South America, Africa and southern Asia, where, to our knowledge, no assessments are currently available in the literature. We recommend an approach that targets representative types of coastal aquifers based on geology (e.g., karst, coastal plains, deltaic) and environmental parameters (e.g., precipitation, temperature). The production of a SGD database and globalisation efforts are necessary to understand controls and changes in SGD on broad sub-regional and continental scales.

Improvements must also be made to techniques used for measurements of SGD, including: the development of new non-invasive methods, measuring and sampling strategies in permeable sea beds, modelling of the different transport processes and their effects on biogeochemical cycles and the development of new dynamic models to explain the porewater flow observed in natural environments.

Management of SGD in coastal areas requires greatly improved knowledge about the importance of hydrological flows. Since SGD is essentially "invisible," the problem that arises from both a management and scientific standpoint is determining how to avoid the error of ignoring an important process or wasting valuable resources on an unimportant issue. Where SGD is a significant factor in maintaining or altering coastal ecosys-

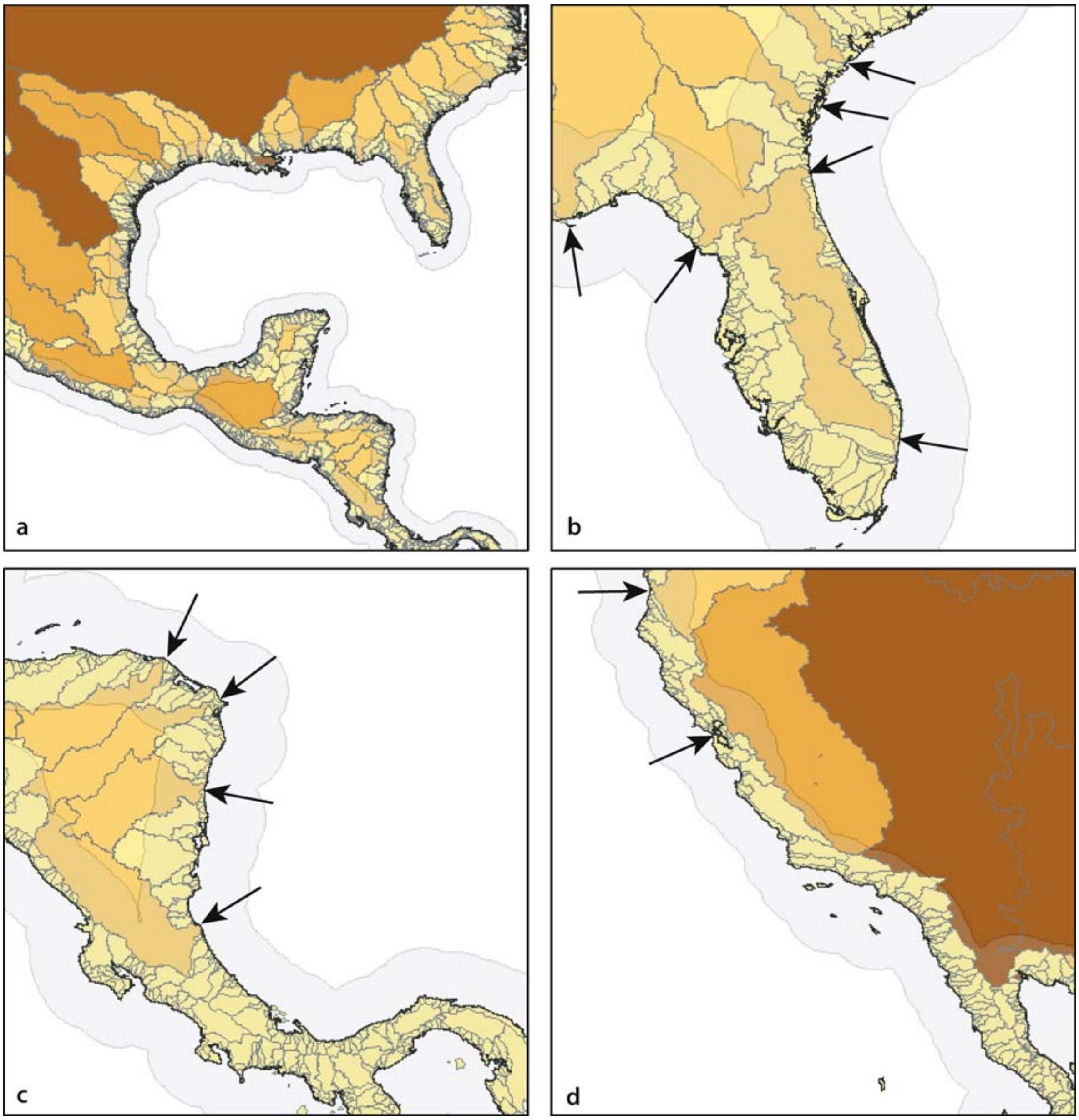


Fig. 5.2. River basins from the coasts of the US and Central America. The transparent grey is a 100 km buffer around the coastline, indicating the approximate extent of the coastal zone. Yellow basins represent those less than 10 000 km^2 in area – the approximate dividing line between "small" and "large" basins. In (**a**), small coastal basins appear numerous, but far from continuous. A close-up view in (**b**) brings the smallest coastal basins into view, and shows how much of the coastline is without the large basin discharges indicated by arrows (e.g., three in all of peninsular Florida). Similarly, in (**c**), it can be seen that the isthmus of Central America contains only small basins – a feature common to many islands and peninsulas. (**d**) shows part of the west coast of Mexico and the US; there are only two large basin discharge points between the tip of Baja California (not shown) and southern Oregon. Many extensive reaches of coastline are dominated completely by inputs from the functionally distinctive smaller basins

tems (terrestrial, estuarine or marine), coastal zone managers will need to consider management of water levels and fluxes through controls on withdrawal or alterations in recharge patterns, as well as groundwater quality management (e.g., through controls on land use and waste disposal). Such major interventions require a sound scientific justification and technical understanding that does not currently exist.

5.4.3 Biogeochemical Budgets

A major challenge in enhancing scientific knowledge and its use for informing management is the issue of spatial heterogeneity and the choice of appropriate scales to use in analysing biogeochemical processes and budgets. It is obvious that with decreasing system size comes increasing heterogeneity among systems. The ocean as a whole is a large system in which most metabolism is accomplished by plankton with relatively rapid biotic turnover rates. Smaller systems in the coastal zone are locally dominated by plankton, benthic micro- and macroalgae, seagrasses, coral reefs and mangroves. These systems differ greatly between one another, and they respond very differently to perturbations. Generalising globally therefore demands that each system type be adequately represented at an appropriate scale for data analysis.

Several other challenges are associated with methodological issues. The first issue involves scaling. Because large systems tend to have longer water exchange times, this can be considered a scaling issue in both space and time. Any budget or inventory approach to assessing the function of aquatic ecosystems needs to deal with two broad classes of material transfer: physical transfer and biotic cycling. As a generality, the physical transfers have a wide dynamic range at small scales. For example, water flow can vary from near stagnant to meters per second (a range of orders of magnitude). As scales get larger, the accumulated physical transfers are smaller – large transfers in one direction tend to be balanced by transfers in the other direction. This balance is required to conserve mass. At small scales, biotic transfers tend to have a much lower dynamic range and these processes also tend to balance at larger scales. However, with an increase in scale, the ability to see small effects of biotic processes grows. More information is needed for small, active systems with short water exchange times while recognising that these systems tend not to yield robust estimates of fluxes.

A second methodological issue concerns the use of ΔDIP as a proxy for organic carbon metabolism. This clearly works in some – but not all – systems. In particular, other reaction pathways, notably sorption and desorption of DIP with respect to sediment particles, interfere with the proxy. This is a particular problem for systems with high mineral turbidity. Yet reliable data simply do not exist to develop a large number of budgets or inventories based on carbon. Either an alternative approach must be found or methods must be developed to modify the DIP budgets.

A third methodological issue involves extrapolation from a relatively small number of budget sites to the global coastal zone. We have used a powerful geo-statistical clustering tool (LOICZView) and data available at a grid scale of 0.5 degrees (areas > 2 000 km^2 for much of the globe). This grid scale is largely dictated by the available spatial data. On land, because most features are both spatially fixed and readily visible, global resolution to 1 km is available for many variables. In the ocean, resolution of geo-spatial data is hampered by the more rapid dynamics of water movement, the limited ability to see and thus describe subsurface features, and the importance of largely invisible chemical characteristics of the water. Most available spatially distributed information is at scales well in excess of 1 degree and interpolated to smaller scales. It is therefore impossible to use such coarsely defined data to extrapolate the characteristics of small coastal features. Some alternative approach must be found.

Successful extrapolation from the LOICZ biogeochemical budget data to the global coastal zone requires three classes of globally available data:

- data for that portion of the land delivering materials to a particular location (system or biogeochemical budget site) in the coastal zone,
- oceanic data adjacent to the system, and
- oceanic data for that system.

For land, data can be obtained from highly resolved remote sensing data. These data can be re-sampled at the scale of the budget system watershed, or catchment, i.e., at a more natural or functional scale than the 0.5 degree grid. Process-based regression models of material fluxes could then be developed for the budget catchments and then extrapolated to the generally coarser and more artificial catchments defined by the 0.5 degree grid. Both the lack of an objective oceanic functional unit equivalent to catchment basins and the crudeness of the oceanic data have so far precluded an equivalent analysis for either the budget systems themselves or the ocean region exchanging with any particular system.

It is clear that there are subject areas that deserve further research and assessment based on collective experience gained by LOICZ. The first area concerns themes and methodological issues, which represent possible revisions or expansions of the LOICZ fundamentals. Additional issues concern the refinement of LOICZ software tools and support. Other possible gaps are (*1*) lack of large river budgets, treatments and actual determination of proportional influence, and (*2*) geographic coverage gaps, such as the North American continent including Arctic, the European Arctic and Central America.

5.5 The LOICZ Contribution

Drawing the outcomes of the LOICZ themes together, and considering the questions they raise, highlights some broad key outcomes from the first phase of LOICZ regarding impacts along the catchment–coast continuum:

1. Land use and cover change, directly or in adaptation to global forcing and related changing societal demands for space, food and water, are driving changes of material fluxes through river catchments to the coastal seas and cause state changes and system impacts.
2. Priorities of drivers and trends that can be expected to generate key coastal issues are urbanisation and increasing demand for water (river regulation) and food (agriculture/fertilizer use).

3. Advancement in mitigating riverine nutrient and contaminant loads to the coastal zone is being accomplished in certain areas such as Europe in time-scales of two decades following policy implementation that targets specific goals for point-source treatment.
4. Costs of "no-response" scenarios that exceed critical thresholds of system function and lead to habitat impact are evident in some sites and are likely to increase.
5. Most of the global coastal zones affected by river input from small and medium-sized catchments are lacking the scientific understanding of catchment coast interaction dynamics and scales as well as the institutional underpinning to cope with increasing pressures.
6. Small and medium-sized catchments and in particular small and low lying island-dominated areas frequently feature the extreme end of DPSI scenarios (e.g., population-density driven water demand and pollution), and there is little evidence for operational mechanisms to take scientifically based management action.
7. Tools and mechanisms to utilize the scientific understanding are available in some areas and are lacking in others. In particular the institutional dimensions of either scientific and management response have proven to be rather ineffective in many regional assessments. However, the key prerequisite to improving this situation is to apply a broad, full-catchment scale to the scientific, assessment and management aspects to adequately address the temporal and spatial complexity of the issues.
8. The overall trend expectation of the driver development affecting coastal seas indicates an accelerated catchment based influence on coastal zones and their functioning.

The key issues identified from the LOICZ work and the scientific framework that has been developed support evolving concepts of integrated management for terrestrial, coastal and marine systems. For example, the UN sponsored Global Environment Facility (GEF) Operational Programme No. 2 gives priority to "the sustainable use of the biological resources in coastal, marine and freshwater ecosystems." The European Union developed the Water Framework Directive that required integrated management strategies to be developed for river basin systems. This has been followed by a Recommendation to all Member States to develop integrated policies, management strategies and plans for the implementation of integrated coastal zone management. These examples illustrate the movement towards more integrated development planning and resources management and the corresponding need for enhanced scientific knowledge and frameworks of the kind LOICZ has been developing to help inform policy, management strategies and planning decisions.

The LOICZ programme also provides an ongoing, adaptive global synthesis that represents an evolving new approach to linking science and management. It has several features that allow it to function in this way, including:

- an adaptive approach to science and management,
- evolving questions,
- long term (ongoing) projects,
- a unique global network of participating scientists and others who have adopted the LOICZ methodologies, and
- ongoing, participatory synthesis to help prioritise future research needs and goals.

5.6 Implications for Management

The first phase of the LOICZ programme provided a valuable scientific framework for studying and integrating a broad range of factors that influence the dynamics of coastal systems and the human use of the resources derived from the functions of those systems. The individual thematic studies presented in the previous chapters have expanded our understanding of the transformation and fate of materials discharged into different coastal environments. While there are constraints imposed by limited understanding of natural variability in climatic conditions and the full impact of human-induced changes on water and material fluxes, *there is now sufficient understanding of these factors to develop new and more holistic frameworks for understanding how coastal ecosystems are responding to human pressures and how we can improve coastal management to respond to these changes.*

The key findings of the thematic studies and their implications for management are:

- *Coastal systems are important to the functioning of the Earth system.*

  Although the coastal zone is only 12% of the surface area of the Earth, coastal systems have been shown to be disproportionately important in the global cycles of nitrogen, phosphorus, and carbon. At local to regional scales, waste and load estimates have been derived, system metabolism has been estimated and tools and a data base of more than 200 coastal sites have been developed and made accessible through a dedicated public website (*http://data.ecology.su.se/MNODE*). Estimates of human pressures on material fluxes and changes in river catchments affecting the coastal seas have been derived at the continental scale for Africa and South America, at the sub-continental scale for Europe and Asia, and for small-island areas of the Caribbean and Oceania. Data and the resulting information and synthesis have been made publicly available (*http://w3g.gkss.de/projects/loicz_basins*). The improved management of human activities affecting material fluxes to and within coastal systems could therefore play a significant role in managing global material cycles and moderating the influence of climate change.

- *Investing in science and management of the coastal zone is highly worthwhile.*

  Coastal ecosystems are complex, productive and critical to human society, and are impacted differentially by human activities. LOICZ identified and quantified the vulnerability of coastal systems to global change impacts. Differences between un-impacted and impacted coastal ecosystems can be significant and can dramatically affect the provision of ecosystem services that support human welfare. The value of ecosystem services derived from the coastal zone is estimated to be large (US$ 17.5 trillion yr^{-1}) and under significant threat. A more certain scientific understanding of coastal processes can help to improve the management of coastal systems, reduce the vulnerability of human activities and enhance the sustainability of public and private investments. Therefore, investing in science and management of the coastal zone makes good economic sense.
- *A broad systems approach is necessary to effectively manage human activities in the coastal zone.*

  The coastal zone is dynamic at multiple time and space scales, but it is possible (at least to some degree) to separate the background "natural" dynamics from changes due to human activities. Resilience and adaptability to change at various rates in the biological and social components of the system are critical to their sustainability. To understand these impacts and to manage effectively the human activities in these systems, we need to adopt a broader "systems" perspective that integrates the interacting biophysical and social dynamics and the multiple temporal and spatial scales involved. To meet some of these needs, a typology system of the coastal zone was developed. Application of this approach also allowed us to understand the previously under-estimated influence of groundwater discharge on coastal systems.
- *Complex scientific information can be synthesized to inform and improve the management of coastal systems.*

  Synthesising the large and complex amount of data available about the coastal zone to address management issues is a daunting task that often hinders effective management. The DPSIR approach is a useful framework for enhancing stakeholder participation and organizing and synthesising knowledge about land-based fluxes and other information important to management of the coastal zone at regional and local scales. Regional/continental scale assessments are a useful complement to the DPSIR approach. The regional river-basin studies have identified a common list of drivers for river basins and have identified key differences in the relative importance of these drivers among regions. For example, the major influence (driver) in temperate climatic zones characterized by industrial development and urbanisation is eutrophication of estuarine and nearshore marine waters. For tropical river basins the main driver for coastal change is change in sediment budgets. For polar climatic zones, the main driver of change is change in climatic conditions. Therefore, the focus of management in each area needs to correspond to what are found to be the major drivers and influences. The DPSIR approach is also iterative, so that as the relative importance of specific drivers changes with time, these "new" conditions can be fed back into the cycle for re-analysis.

  Although there are major river systems discharging into the coastal zone, most of Earth's coastline is characterized by small heterogeneous systems that contribute disproportionately to carbon and nutrient budgets and have high potential to be influenced by human activities. Therefore, management to mitigate the impacts of human activities on small, semi-enclosed systems, as well as on large catchment systems, is an important objective.

5.7 The Future of LOICZ

The science of LOICZ has focussed on the measurement of biogeochemical fluxes into and within the coastal zone and shown these fluxes to be important and relevant to global environmental change (GEC) science because:

- biogeochemical fluxes of CO_2 and trace gases are the key variables for scaling up to global climate change,
- biogeochemical variables are the key constituents for connections across coastal boundaries i.e. from catchment to coast, from coast to ocean and from coast to atmosphere,
- biogeochemical fluxes include primary production, which underpins ecosystems and renewable resources,
- water and sediment quality determine distribution of key habitats and affect human amenity and use, and
- biogeochemical processes and cycles include key positive and negative feedbacks in coupled coastal systems, which determine thresholds and boundaries for system resilience.

5.7.1 The Future Challenges for LOICZ

From an initial investigation of process and of specific marine and terrestrial systems, LOICZ has arrived at a point of improved systematic understanding of the controls and influences on coastal fluxes. We can now look forward to the next steps to inter-calibrate and combine the results of the converging threads of understanding developed during the first phase of LOICZ. The recommendations below reflect the need and opportunities for advancing the process, recognising the multiplicity of processes, changes and forces (natural and human-driven) across the dynamic and heterogeneous global coastal zone.

1. *Integrated and multidisciplinary team approaches*. While often stated, there is imperative for *genuine* research collaboration among natural, social and economic disciplines. Existing global examples show clear knowledge benefits from such team interactions. New approaches are needed to assist team actions, such as the DPSIR framework, and "wiring diagrams" used in IGBP for the development of cross-cutting projects.
2. *Targeted research*. Thematic and programmatic research approaches as practised in "*post-Normal*" *science* (Funtowicz and Ravetz 1992, 1993, Ravetz and Funtowicz 1999) address the management of complex science-related issues by focusing on aspects of problem-solving that tend to be neglected in traditional accounts of scientific practice: uncertainty, value-loading and a plurality of legitimate perspectives. It provides a coherent explanation of the need for greater participation in science-policy processes, based on the new tasks of quality assurance in these problem-areas, and is an alternative approach to coastal zone research compared with the traditional, fragmented approach of task-based, disciplinary or sectoral efforts. Questions of different temporal and spatial scales need urgent consideration along with new tools for assessment and measurement across scales and within socio-economic research. A focus should be placed on understanding whole ecosystem functioning and forcing, vulnerability and risk, changing pressures, feedbacks and integration of forcings. Improved models (conceptual, numeric, deterministic, probabilistic) for top-down and bottom-up approaches are required. Efforts on socio-economic research need to be greatly increased.
3. *Synthesis and integration of information*. New scientific enterprise is always welcome but better use needs to be made of existing data, information and knowledge; bodies funding research need to shift policies in this regard. New tools, approaches and efforts should be exerted for the synthesis of scientific data into information and knowledge, and outcomes need to be made accessible to users and the community. Along with further concerted effort to engage with users, science programmes should include a clear strategy for communication and delivery of information.
4. *Regionality*. Thematic projects, synthesis and integration should be directed to assessment at regional scales to more fully understand the tapestry of the coastal zone and to resolve response and management options that address the vital transboundary elements. The application of common methodologies will increase regional integration of information and options.
5. *Non-linearity of processes (feedbacks and thresholds)*. The non-linear relationships of forcing and function are apparent in the coastal zone. New concepts, tools and approaches are required, to encompass non-linearity in modelling and predictions, scenario-building and vulnerability-risk assessments.
6. *Monitoring and indicators of functions and changes*. Proxies for measurement of processes and variability, and indicators of system function and response, are required to better understand and measure change and the effectiveness of management and policy applications.
7. *Improved databases and access*. There is need for concerted efforts to develop stronger datasets, to fill critical data gaps and to improve cross-referencing of datasets so that stronger integration can be achieved. Improved access to existing data and wider accessible to datasets would reduce duplication in coastal assessments.
8. *Capacity building*. Underpinning future research enterprise is the need for continuing and enhanced capacity-building in both science and management training and awareness.

Therefore, the challenges for future GEC research on the coastal zone are to develop understanding and tools for the derivation, differentiation and quantification of anthropogenic drivers and global environmental pressures. This distinction is essential to determine appropriate management options for land-ocean interactions in the coastal zone. Consequently, future research goals for LOICZ are aimed to overcome traditional disciplinary fragmentation, in particular between natural and human-dimension sciences, in order to focus on the primary issues of sustainable human use of coastal systems in respect to vulnerability of coasts and risks for human uses.

5.7.2 The Potential for LOICZ to Contribute to Future Coastal Management Challenges

The coastal regions of the globe will form the focus of future growth of population, development of settlements, and expansion and diversification of economic activities. Coastal regions already provide a significant proportion of the goods and services that support the livelihoods of coastal communities and national economies. These development pressures will bring major changes to coastal ecosystems and the role they play in global environmental change. There will also be increased risks to human societies from natural and man-induced natural hazards. These risks can be minimised through sound planning and management of development processes.

The LOICZ programme has provided a wealth of information that could be used to strengthen the conceptual basis for integrated coastal management and associated development and spatial planning. For example, the work on material fluxes and river basins has demonstrated strong linkages between the management of small to medium sized catchments and impacts on coastal and nearshore marine systems, the supply of natural resources they sustain, and functions such as buffering of storm surges. The DPSIR framework has demonstrated how such complex information from the natural and social sciences can be integrated to identify the core drivers that influence the management of river systems and the response of coastal systems. This work could be used to expand the conceptual basis of existing policy instruments, for instance, the EU Water Framework Directive, to encompass material fluxes, surface and ground water flows, and energy and other factors that will influence sustainable human use of coastal areas. This would strengthen such policy and management instruments by supporting the development of integrated river basin management and their effectiveness in supporting the management of coastal and marine areas.

The challenge is to make available the results of the LOICZ science in a format and constitution that provides a means and route to contribute to the formulation and implementation of policies, management strategies and implementation arrangements that are appropriate to the different regions of the world. Although further research is needed to refine the results of the thematic studies and to strengthen their utility, there is sufficient understanding of the role of coastal systems in global environmental change to develop a constructive dialogue with policy ma-kers, planners and managers. That is a question of effective communication of science and one that the next phase of the LOICZ programme will address with great vigour.

References

Barth F, Fawell J (2001) The water framework directive and European water policy. Ecotoxicology and Environmental Safety 50: 103–105

Biesecker A (1996) The market as an instituted realm of social action. Bremer Diskussionpapiere zur Socialökonomie 1, University of Bremen, Bremen

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Crossland CJ (2000) Improved strategies for linking coastal science and users. In: Pacyna JM, Kremer HH, Pirrone N, Barthel K-G (eds) Socio-economic aspects of fluxes of chemicals into the marine environment – workshop report, Keller, Norway 8–10 March 1999. EURO 19089. European Commission, Luxembourg, pp 199–210

EEA (1998) Europe's environment: the second assessment. European Environment Agency, Copenhagen

Funtowicz SO, Ravetz JR (1992) Risk management as a postnormal science. Risk Analysis 12(1):95–97

Funtowicz SO, Ravetz JR (1993) Science for the post-normal age. Futures 25(7): 739–755

Humphrey S, Burbridge P, Blatch C (2000) US lessons for coastal management in the European Union. Mar Pol 24:275–286

Kaika M, Page B (2002) The making of the EU water framework directive: shifting choreographies of governance and the effectiveness of environmental lobbying. University of Oxford, School of Geography and the Environment. Economic Geography Research Group. WPG 02-12

Kallis G, Butler D (2001) The EU water framework directive: measures and implications. Water Policy 3: 125–142

Kremer HH, Pirrone N (2000) Coastal zone management and integration of natural and socio-economic zones. Report of ELOISE Working Group 4. EU Commission, EUR 18599 – European Land-Ocean Interaction Studies, ELOISE, Implementation Report, Phase II, pp 56–68. European Commission, Luxembourg

Ledoux L, Burgess D (2002) Science for water policy: the implications of the water framework directive. Proceedings of the SWAP Euroconference, 1–4 September 2002. University of East Anglia, Norwich, UK

Meybeck M (1982) Carbon, nitrogen and phosphorus transport by world rivers. American Journal of Science 282:401–450

Meybeck M, Ragu A (1997) River discharges to the oceans: an assessment of suspended solids, major ions and nutrients. GEMS/EAP Report

Milliman JD, Meade RH (1983) World-wide delivery of river sediment to the ocean. Journal of Geology 91:1–21

Murray CN, Bidoglio G, Zaldivar J, Bouraoui F (2002) The water framework directive: the challenges of implementation for river basin–coastal zone research. Fresenius Environmental Bulletin 11(9):530–541

Ravetz J, Funtowicz S (1999) Post-normal science – an insight now maturing. Futures 31(7):641–646

Salomons W, Bayne B, Heip CH, Turner RK (1995) Changing estuarine and coastal environment: sustainability and biodiversity in relation to economic aspects. Workshop report EERO-GKSS, Geesthacht, Germany

Smith SV, Hollibaugh JT (1993) Coastal metabolism and the oceanic organic carbon balance. Reviews of Geophysics 31:75–89

Smith SV, Renwick WH, Buddemeier RW, Crossland CJ (2001) Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15(3):697–707

Talaue-McManus L, Kremer HH, Marshall Crossland JI (2001) Biogeochemical and human dimensions of coastal functioning and change in Southeast Asia. Final report of the SARCS/WOTRO/LOICZ project 1996–1999. LOICZ Reports and Studies. LOICZ IPO, Texel, The Netherlands, No. 17

Turner RK, Adger WN, Lorenzoni I (1998) Towards integrated modelling and analysis in coastal zones: principles and practice. LOICZ Reports and Studies. LOICZ IPO, Texel, The Netherlands, No. 11

Wilson MA, Costanza R, Boumans R, Liu S (2003) Integrating assessment and valuation of ecosystem goods and services provided by coastal systems. In Wilson JG (ed) The intertidal ecosystem. Royal Irish Academy, Dublin, pp 1–28

Appendix

A.1 LOICZ Reports and Studies and Key Publications

A.1.1 LOICZ Reports and Studies Series

(published as LOICZ Reports and Studies, LOICZ International Project Office, Texel, The Netherlands)

Coastal Seas: A Net Source of Atmospheric Carbon Dioxide?

Kempe S. No. 1, 1995

River Discharge to the Sea: A Global River Index (GLORI):

Milliman JD, Rutkowski C, Meybeck M. No. 2, 1995

LOICZ Typology: Preliminary Versions for Discussion:

Anon. No. 3, 1995

Coastal Zone Resource Assessment Guidelines:

Turner RK, Adger WN. No. 4, 1996

LOICZ Biogeochemical Modelling Guidelines:

Gordon DC, Boudreau PR, Mann KH, Ong J-E, Silvert WL, Smith SV, Wattayakorn G, Wulff F, Yanagi T. No. 5, 1996

LOICZ Data and Information Systems Plan:

Boudreau PR, Geerders PJF, Pernetta JC. No. 6, 1996

First Report of the JGOFS/LOICZ Continental Margins Task Team:

Hall J, Smith SV (eds). No. 7, 1996

Groundwater Discharge in the Coastal Zone:

Buddemeier RW (ed). No. 8, 1997

International Workshop on Continental Shelf Fluxes: Carbon, Nitrogen and Phosphorus:

Hall J, Smith SV, Boudreau PR (eds). No. 9, 1997

Comparison of Carbon, Nitrogen and Phosphorus Fluxes in Mexican coastal Lagoons:

Smith SV, Ibarra-Obando S, Boudreau PR, Camacho-Ibar VF (eds). No. 10, 1997

Towards Integrated Modelling and Analysis in Coastal Zones: Principles and Practice:

Turner RK, Adger WN, Lorenzoni I. No. 11, 1998

Australasian Estuarine Systems: Carbon, Nitrogen and Phosphorus Fluxes:

Smith SV, Crossland CJ (eds). No. 12, 1999

Mexican and Central American Coastal Lagoon Systems: Carbon, Nitrogen and Phosphorus Fluxes (Regional Workshop II):

Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 13, 1999

Estuarine Systems of the South China Sea: Carbon, Nitrogen and Phosphorus Fluxes:

Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 14, 2000

Estuarine Systems of the South American Region: Carbon, Nitrogen and Phosphorus Fluxes:

Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 15, 2000

Estuarine Systems of the East Asia Region: Carbon, Nitrogen and Phosphorus Fluxes:

Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 16, 2000

Biochemical and Human Dimensions of Coastal Functioning and Change in South East Asia:

Talaue-McManus L, Kremer HH, Marshall Crossland JI (eds). No. 17, 2001

Estuarine Systems of Sub-Saharan Africa: Carbon, Nitrogen and Phosphorus Fluxes:

Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 18, 2001

Coastal and Estuarine Systems of the Mediterranean and Black Sea Regions: Carbon, Nitrogen and Phosphorus Fluxes:

Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 19, 2001

Estuarine Systems of Africa (Regional Workshop II): Carbon, Nitrogen and Phosphorus Fluxes:

Dupra VC, Smith SV, David LT, Waldron H, Marshall Crossland JI, Crossland CJ (eds). No. 20, 2002

South American Basins: LOICZ Global Change Assessment and Synthesis of River Catchment-Coastal Sea Interaction and Human Dimensions:

De Lacerda LD, Kremer, HH, Kjerfve B, Salomons W, Marshall Crossland JI, Crossland CJ (eds). No. 21, 2002

LOICZ/UNEP Regional Synthesis Workshops: Australasia-Asia, the Americas, Africa-Europe. Summary report and compendium:

Buddemeier RW, Crossland CJ, Maxwell BA, Smith SV, Swaney DF, Bartley JD, Misgna G, Smith C, Dupra VC, Marshall Crossland JI (eds). No. 22, 2002

Estuarine Systems of the Latin American Region and of the Arctic Region: Carbon, Nitrogen and Phosphorus Fluxes:

Camacho-Ibar VF, Dupra VC, Wulff F, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 23, 2002

The Role of the Coastal Zone in the Disturbed and Undisturbed Nutrient and Carbon Cycles:

Buddemeier, RW, Smith SV, Swaney DP, Crossland CJ (eds). No. 24, 2002

African Basins: LOICZ Global Change Assessment and Synthesis of River Catchment-Coastal Sea Interaction and Human Dimensions:

Arthurton RS, Kremer HH, Odada E, Salomons W, Marshall Crossland JI (eds). No. 25, 2002

East Asia Basins: LOICZ Global Change Assessment and Synthesis of River Catchment-Coastal Sea Interaction and Human Dimensions:

Hong GH, Kremer HH, Pacyna J, Chen C-TA, Behrendt H, Marshall Crossland JI (eds). No. 26, 2002

Caribbean Basins: LOICZ Global Change Assessment and Synthesis of River Catchment-Coastal Sea Interaction and Human Dimensions and a Desktop Study of Oceania Basins:

Kjerfve B, Wiebe WJ, Kremer HH, Salomons W, Marshall Crossland JI (Caribbean); Morcom N, Harvey N, Marshall Crossland JI (Oceania) (eds). No. 27, 2002

A.1.2 Key Publications from LOICZ

Coral Reefs and Environmental Change – Adaptation, Acclimation or Extinction:

Buddemeier RW, Lasker HR (eds). American Zoologist 39(1): 1–183, 1999

Perspectives on Integrated Coastal Management:

Salomons W, Turner RK, de Lacerda LD, Ramachandran S (eds). Springer, Berlin, 1999

Scientific Report on Socio-economic Aspects of Fluxes into the Marine Environment:

Pacyna JM, Kremer HH, Pirrone N, Barthel K-G (eds). EU Monograph Series EUR 19089, EU Commission, Brussels, 2000

Land-Ocean Interactions in the Coastal Zone:

Crossland CJ, van Raaphorst W, Kremer HH (eds). Journal of Sea Research Special Issue 46(2):85–185, 2001

Nearshore and Coastal Oceanography. ELOISE – European Land Ocean Interaction:

Huntley DA, Oltman-Shay J, Murray N (eds). Continental Shelf Research 21(18–19):1919–2183, 2001

Regimes of Regional and Global Coastal Change:

Kremer HH (ed). Regional Environmental Change 3(1–3):1–117, 2002

Supply and Flux of Sediment along Hydrological Pathways: Anthropogenic Influences at the Global Scale:

Syvitski JPM (ed). Global and Planetary Change 39(1–2):1–199, 2003

Submarine Groundwater Discharge:

Burnett WC, Chanton JP, Kontar E (eds). Biogeochemistry 66(1–2): 1–202, 2003

River Catchment-Coastal Sea Interactions and Human Dimensions:

Kremer HH (ed). Regional Environmental Change 4(1):1–76, 2004

European Catchments: Catchment Changes and their Impact on the Coast:

Salomons W. Institute for Environmental Studies, Vrije University, Amsterdam, The Netherlands, 2004

Managing European Coasts: Past, Present and Future:

Vermaat JE, Ledoux LC, Salomons W, Turner RK. Springer, Berlin, Heidelberg, New York, 2005

A.2 Acronyms and Abbreviations

APN	Asia-Pacific Network for Climate Change
ARI	average recurrence interval
BAU	business-as-usual
CAP	Common Agricultural Policy (EU)
CMTT	Continental Margins Task Team (a joint project between LOICZ and JGOFS)
COOP	Coastal Ocean Observing Programme (the coastal module of GOOS)
CPR	continuous plankton recorder

CPUE	catch per unit effort
CVI	coastal vulnerability index
denit	denitrification
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
DINAS-COAST	Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-level Rise
DIP	dissolved inorganic phosphorus
DIVERSITAS	an international programme on biodiversity science
DMS	dimethyl sulphoxide
DOC	dissolved organic carbon
DON	dissolved organic nitrogen
DOP	dissolved organic phosphorus
DPSIR	Driver-Pressure-State-Impact-Response
DV	dredged volume
EEA	European Environment Agency
ENSO	El Nino-Southern Oscillation
ERA	eastern Russian coast
EU	European Union
EU-BIOGEST	EU-ELOISE project: Biogases Transfers in Estuaries
EU-ELOISE	European Union – European Land-Ocean Interaction Studies
FAO	Food and Agriculture Organisation
GEF	Global Environment Facility
GESAMP	Group of Experts on the Scientific Prospects of Marine Environmental Protection
GHG	greenhouse gas
GIA	glacio-isostatic adjustment
GIS	geographical information system
GIWA	Global International Water Assessment
GM	geometric mean
GNP	gross national product
GOOS	Global Ocean Observing System
Gt	gigatonne
HAB	harmful algal bloom
HELCOM	Helsinki Commission
IAI	Inter-Americas Institute
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
ICZM	integrated coastal zone management
IOC	Intergovernmental Oceanographic Commission of UNESCO
IOI	International Ocean Institute
IPCC	Intergovernmental Panel on Climate Change
JGOFS	Joint Global Ocean Flux Study; a core project of IGBP
KNAW	Royal Netherlands Academy of Arts and Sciences
Royal NIOZ	Royal Netherlands Institute for Sea Research
LME	large marine ecosystem
LOICZ	Land-Ocean Interactions in the Coastal Zone core project of IGBP
LOICZ IPO	LOICZ International Project Office
LOIS	Land-Ocean Interaction Study, United Kingdom
NAO	North Atlantic Oscillation
NEM	net ecosystem metabolism
nfix	nitrogen fixation
NIWA	National Institute of Water & Atmospheric Research, New Zealand
NOAA	National Ocean and Atmosphere Administration, United States of America
NSF	National Science Foundation, United States of America
NWO	Netherlands Organisation for Scientific Research
OBIS	Ocean Biogeographic Information System
OcW	Ministry of Education, Culture & Science, The Netherlands
OECD	Organisation for Economic Cooperation and Development
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
p	primary production
PAGES	Past Global Changes core project of IGBP
PAH	poly-aromatic hydrocarbon
PCB	poly-chlorinated benzene
PET	potential evapo-transpiration
PNG	Papua New Guinea
psu	practical salinity unit
RI	retention index
RIKZ	Water Management, Ministry for Transport and Public Works and Water Management, The Netherlands
RMA	reduced major axis
RO	runoff
SARCS	Southeast Asia Regional Committee for START
SCOR	Scientific Committee on Oceanic Research
SGD	submarine groundwater discharge
SGR	submarine groundwater recharge
SPE	submarine porewater exchange
SPREP	South Pacific Regional Environmental Programme
SRES	Special Report on Emission Scenarios
SSC	Scientific Steering Committee
SST	sea surface temperature
START	Global Change System for Analysis, Research and Training
SURVAS	Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies
TIMS	thermal ionisation mass spectrometry
UNCED	United Nations Conferences on Environment and Development
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme

UNESCO	United Nations Educational, Scientific and Cultural Organisation
WCRP	World Climate Research Programme
WFD	Water Framework Directive (WFD)
WOTRO	Netherlands Foundation for the Advancement of Tropical Research
WRA	western Russian coast
WVS	world vector shoreline

Index

T

U

V

W

X

Y

Z