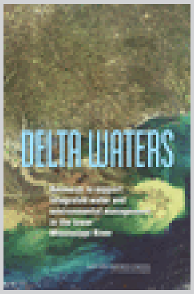

Delta Waters: Research to Support Integrated Water and Environmental Management in the Lower Mississippi River

ISBN
978-0-309-29216-0

140 pages
6 x 9
PAPERBACK (2013)

Committee on Strategic Research for Integrated Water Resources Management; Water Science and Technology Board; Division on Earth and Life Studies; National Research Council

DELTA WATERS

Research to support integrated water and environmental management in the lower Mississippi River

Committee on Strategic Research for
Integrated Water Resources Management

Water Science and Technology Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this study was provided by The Water Institute of the Gulf under Agreement No. BRAF-2012-NRC-CG. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-29216-0
International Standard Book Number-10: 0-309-29216-6

Cover: Image courtesy of the European Space Agency (ESA).

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON STRATEGIC RESEARCH FOR INTEGRATED WATER RESOURCES MANAGEMENT

JAMES L. WESCOAT, Jr., *Chair*, Massachusetts Institute of Technology
XIMING CAI, University of Illinois, Urbana-Champaign
G. MATHIAS KONDOLF, University of California, Berkeley
BEN R. HODGES, University of Texas, Austin
SAMANTHA B. JOYE, University of Georgia, Athens
WILLIAM M. LEWIS, University of Colorado, Boulder
LEONARD A. SHABMAN, Resources for the Future, Washington, DC
EELCO VAN BEEK, University of Twente, Netherlands

NRC Staff

JEFFREY JACOBS, Study Director
MICHAEL J. STOEVER, Research Associate
ANITA A. HALL, Senior Program Associate

WATER SCIENCE AND TECHNOLOGY BOARD

GEORGE M. HORNBERGER, *Chair*, Vanderbilt University, Nashville, Tennessee
LISA ALVAREZ-COHEN, University of California, Berkeley (through June 2013)
EDWARD J. BOUWER, Johns Hopkins University, Baltimore, Maryland
YU-PING CHIN, Ohio State University, Columbus
M. SIOBHAN FENNESSY, Kenyon College, Gambier, Ohio
BEN GRUMBLES, Clean Water America Alliance, Washington, DC
GEORGE R. HALLBERG, The Cadmus Group, Watertown, Massachusetts
KENNETH R. HERD, Southwest Florida Water Management District, Brooksville, Florida (through June 2013)
CATHERINE L. KLING, Iowa State University, Ames
DEBRA S. KNOPMAN, RAND Corporation, Arlington, Virginia
LARRY LARSON, Association of State Floodplain Managers, Madison, Wisconsin
RITA P. MAGUIRE, Maguire & Pearce PLLC, Phoenix, Arizona
DAVID I. MAURSTAD, OST, Inc., McLean, Virginia
DAVID H. MOREAU, University of North Carolina, Chapel Hill (through June 2013)
DONALD I. SIEGEL, Syracuse University, New York (Chair through June 2013)
ROBERT SIMONDS, The Robert Simonds Company, Culver City, California
FRANK H. STILLINGER, Princeton University, Princeton, New Jersey
MARYLYNN V. YATES, University of California, Riverside
JAMES W. ZIGLAR, SR., Van Ness Feldman, Washington, DC

Staff

JEFFREY JACOBS, Director
LAURA J. EHLERS, Senior Program Officer
STEPHANIE E. JOHNSON, Senior Program Officer
M. JEANNE AQUILINO, Financial and Administrative Associate
MICHAEL J. STOEVER, Research Associate
ANITA A. HALL, Senior Program Associate

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Gregory W. Characklis, University of North Carolina; Gerald E. Galloway, Jr., University of Maryland; Ti Le-Huu, Bangkok, Thailand; Daniel P. Loucks, Cornell University; Lester A. Snow, California Water Foundation, Sacramento; Frank H. Stillinger, Princeton University; Henry J. Vaux, Jr., University of California (emeritus), Oakland.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Michael Kavanaugh, Geosyntech Consultants (Oakland, CA), appointed as report Monitor by the NRC Report Review Committee, and A. Dan Tarlock, Chicago Kent College of Law, appointed as report Coordinator by the NRC Division on Earth and Life Studies. Appointed by the National Research Council, they were responsible for ensuring that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

Deltaic environments are some of the world's most biologically rich, geophysically dynamic, and socially precarious landscapes, even under ordinary circumstances. Sedimentation, erosion, subsidence, and salinity flux are continuous processes, which occasionally are punctuated by flooding, coastal storm surges, and environmental hazards. The Mississippi River delta is the product of avulsive flooding, in which a river leaves its channel, and migrates to another channel. On somewhat longer geologic time scales, the lower Mississippi River has migrated back and forth across its large delta, changing and shifting the large amounts of sediments it transports, and creating its current distinctive landforms and structure.

"Working coasts" like the Mississippi River delta adjust to and reap the fruits of these rich environmental systems, while accelerating some of the hazardous processes of erosion, flood damage, subsidence, and wetland loss. In addition to centuries of local knowledge, there is a wealth of deltaic research associated with water resources management in the lower Mississippi River, and also a need for new knowledge about emerging problems and challenges.

Water and environmental resources managers in the lower Mississippi River and its delta by no means are alone in facing these challenges, and indeed they are addressing them in new ways with the enthusiastic and ambitious adoption of the Louisiana 2012 Coastal Master Plan. The state's Master Plan is very action-oriented and, at the same time, prompts important research questions on human-environment dynamics in the delta. Examples of this research would include monitoring and assessing outcomes of large-scale proposed river water and sediment diversion projects, in the near term, and increasingly integrative research in the longer term.

Placed in a larger, global perspective, research on integrated water management in the Lower Mississippi River bears comparison with issues faced and addressed in other large deltas around the world. What insights might they offer for the Mississippi delta, and what might the Mississippi delta offer in scientific understanding and expertise for other regions?

This report's sponsor, The Water Institute of the Gulf (Water Institute), asked the National Research Council's Water Science and Technology Board to address these questions in this study. The Water Institute is a scientific organization in the Mississippi River delta established in 2011 with a focus on water and environmental resources, which will be informed and inspired in part by comparative international inquiry on large deltaic regions. We thank the Water Institute for its encouragement to think at a higher level about future research questions, both in the Mississippi River delta and in potential research connections with other deltas around the world.

We are grateful to experts who shared their knowledge about the Mississippi River delta. These include guest speakers at our 2012 meetings in Baton Rouge and Washington (see Appendix A), reviewers who helped greatly improve the report (listed below), and the NRC staff who provided leadership from beginning to end. Study director and Water Science and Technology Board director Jeffrey Jacobs has written a comparative paper on the Mississippi and Mekong rivers and provided expertise and guidance to the committee. Laura Ehlers served as study director when the project began, and oversaw organization of the committee's first meeting and helped launch the project. Anita Hall and Michael Stoever ensured smooth logistics and provided editorial guidance throughout.

I offer my personal thanks to the committee members who prepared this report. It was an intellectual and personal pleasure to work together. The report was able to include many but not all ideas that committee members would have liked to include. In the course of this study, we found common ground in the pragmatic needs of the current situation in the lower Mississippi River delta, and an expansive scope for comparative research that can help advance large deltaic water and environmental management in the lower Mississippi River and in its engagement with other regions and peoples around the world. It is toward that fine balance between inquiry at home and around the world that we devote this study.

James L. Wescoat, Jr.

Contents

Summary

Water and related environmental resources have been crucial in the exploration, settlement, and development of the lower Mississippi River and its delta region. From the great prehistoric upstream riverfront engineering works at Poverty Point, to the mobile shell mound settlers of lower distributaries, human populations have adjusted to and transformed their deltaic environments. The City of New Orleans was settled and developed near the mouth of the Mississippi River as a port and a strategic site for access to the river and the heart of the continent. The Mississippi River system and its coastal aquifers provide natural water supplies for New Orleans, Baton Rouge, and other communities. The region has an abundance and diversity of fisheries that support household and commercial livelihoods.

In addition to valuable water-related resources, the region also is subject to Mississippi River floods in spring and summer, and to Gulf of Mexico hurricanes in late summer and fall. There is a long, fascinating history of human efforts to cope with and reduce the effects of these natural hazards, ranging from pre-European inhabitants seeking areas of higher ground for sites of settlement and transportation routes, to modern-day, massive levees and drainage systems along the lower Mississippi River, other water control structures and spillways, and extensive hurricane protection structures within and across the greater New Orleans metropolitan area.

Given the prominence and persistence of natural hydrologic hazards, many early water-related studies and activities in this region focused on hydrology, hydraulics, and engineering, such as the competing studies of Mississippi River hydrology and engineering by Andrew Humphreys and

Charles Ellet in the nineteenth century. Over time, research advanced on related land, water, ecological, and socioeconomic resources—from sediment and settlements to wetlands, biodiversity, and biogeochemistry. There is an extensive research network of universities, agencies, and civil society organizations in the region that have been focusing on these complex water and environmental processes in the delta.

Hurricane Katrina in 2005 was one of the nation's worst storm-related disasters, and in its wake there were numerous investigations and reports that offered both retrospective analyses and alternatives for better addressing risks associated with hurricanes. There was an especially strong interest in comparing New Orleans' coastal protection approach and system to that of the Netherlands. U.S. water experts and decision makers made numerous visits to the Netherlands to assess approaches that might profitably be shared or adapted back in the United States.

It was in this setting that the Water Institute for the Gulf (Water Institute) was established in 2011 and began its operations in 2012. The Water Institute was established with seed money from the State of Louisiana and from the Baton Rouge Area Foundation. The Water Institute aims to provide the state of Louisiana with a central point of scientific capacity to help the state better build a variety of ecosystem restoration and hurricane protection projects. It intends to collaborate with scientists and engineers from around the world, and in doing so, to create a center of scientific excellence that will serve communities throughout the Gulf Coast and beyond. For more information on The Water Institute, its activities, and future plans see http://thewaterinstitute.org/.

The following report was authored by the National Research Council *Committee on Strategic Research for Integrated Water Resources Management*. The committee's statement of task was divided into three topics: (1) common problems and challenges in lower river and deltaic systems, (2) strategic research for integrated water resources management, and (3) transferring and applying scientific knowledge from the lower Mississippi River to other deltaic regions (the report's full statement of task is presented in Chapter 1, Box 1-1). The major sections in this Summary track these three areas as follows: the section on Common Problems and Challenges addresses topic 1 above; sections on Strategic Research for Integrated Water and Environmental Management, Science-Policy Analysis, and Research Coordination and Organizational Options address topic 2 above, and the final section on Comparative International Water Research addresses topic 3 above. First, some comments on the nature of this report's statement of task and its main conclusions are in order.

This report's statement of task requests the NRC committee to offer advice for setting research priorities to support integrated water resources management in lower river and deltaic systems. The report thus has a strong science research program emphasis. Much of the advice herein is based upon the committee's collective expert judgment, and not necessarily detailed review of specific bodies of science, or testing of hypotheses. Research directions thus are presented in the form of promising alternatives and opportunities open to the Water Institute, as opposed to conclusive or definitive science-based recommendations and organizational imperatives. This report does not identify priorities among these many opportunities, but the final chapter provides comments regarding a process for prioritization.

A central concept in this report's statement of task—Integrated Water Resources Management (IWRM)—has various, sometimes contested, meanings in the United States, Europe, and elsewhere that could have a bearing on this report's comparative dimensions. Rather than engaging these ongoing and unresolved debates, the report invokes the IWRM concept selectively with respect to specific studies and programs. For the broader purposes of this report, the study topic is rephrased as integrated water and environmental management (without capitalization or acronym).

The Water Institute's goals to become a credible center for scientific research and advice for the lower Mississippi River, Gulf region, and beyond, will not be realized overnight. Therefore this report offers a range of recommendations that could be implemented over different time scales, ranging from near-term activities, to medium- and longer-term activities and areas of emphasis that would require years to further conceptualize and implement.

COMMON PROBLEMS AND CHALLENGES IN LARGE DELTAS

This report's statement of task calls for identification of key challenges of integrated water and environmental management in large deltaic systems, and for identification of types of research that can contribute to meeting those challenges. This first topic also calls for identification of other large deltaic systems in the world that may provide analogues for integrated water resources management in the lower Mississippi River delta.

The introductory chapter of this report reviews the evolution and trajectory of integrated water and environmental management, including IWRM, in the United States, Europe, and developing regions of the world. The second chapter of the report then turns to Common Problems and Challenges. It begins with a perspective on Mississippi River delta issues, which led to identification of numerous "Agents of Change," each of which has partial analogues in other major deltas of the world. These agents of change range from hydroclimatic variability to sediment transport, land development, and water management.

It is important to stress that the base case of these analogues, for present purposes, is the lower Mississippi River delta. Discussion of each agent of change begins, not with a problematic deltaic water phenomenon in general, but rather with its manifestation and importance in the Mississippi River delta. This is followed by brief identification of recent international studies that can help identify analogues that may have relevance for the Mississippi delta.

Interdependence among agents of change, and geographic differences among deltas of the world, led to a strong sense of the importance of a broad human-environmental systems approach to integrated water management in deltaic regions. These initial investigations yielded the following observations about a systems approach to deltaic challenges and analogues:

- **Research on deltaic "analogues" focuses first on a base case, which in this study is the Mississippi River delta. It then may examine specific agents of change, i.e., by constructing problem-driven partial international analogies, set within a systems framework, to help advance the theory and practice of integrated water and environmental management.**
- **Each of the agents of change considered in this report has received substantial scientific attention, yet potentially entails numerous unmet research needs. These individual agents of change are highly interdependent. It thus is not possible to fully explain complex problems (e.g., coastal land loss in Louisiana), through research on individual agents alone. Nor is it possible to meaningfully advance integrated water and environmental management through a reductionist approach of the sort adopted in some scientific investigations and projects, as compared with a systems approach.**
- **Large deltas of the world vary so greatly that international comparisons focused solely on one or a few agents of change are not likely to provide comparisons robust enough to advance the theory and practice of integrated water and environmental resources management in the Mississippi River delta.**
- **It therefore is important to develop and employ a "human-environmental systems approach," grounded in the Mississippi delta base case—and to use that systems approach to seek partial analogues with other large deltas in ways that inform, inspire, and challenge integrated water and environmental management in the lower Mississippi River delta.**

The remaining chapters build upon these findings by focusing on systemic research challenges and opportunities for the Water Institute.

STRATEGIC RESEARCH FOR INTEGRATED MANAGEMENT

Of the many unmet research needs and promising approaches in the Mississippi River delta and comparable deltas of the world, some will have greater priority than others. A strategic approach in this context is one that balances attention to emerging research needs with deliberation about longer-term research planning. The findings below strive to illustrate this balanced approach.

Some of the research opportunities identified below could be pursued separately, or they could be combined into a single broader study. For example, the report discusses the value of preparing a synthesis of knowledge about the Mississippi River delta; and conducting a condition of the delta assessment that would yield a baseline study for future restoration experiments. For clarity, they are presented below separately, although it would also be possible to combine them.

Research Synthesis

There is to our knowledge no synthetic overview of the current state of knowledge on integrated water and environmental management in the Mississippi River delta from which further research in the region, or comparison with other deltaic regions, could benefit. Such a synthesis of current knowledge could put forth broadly useful information as well as interpretations and hypotheses that have been tested, and that currently may be either widely accepted or controversial. Scientists in several deltas around the world—including the Rhine and Mekong—have undertaken similar types of studies.

Enormous bodies of research on the Mississippi River delta have been undertaken by many institutions. Nevertheless, there does not appear to be a comprehensive published "institutional map" of that research (i.e., a systematic diagram of delta research organizations, major programs, and archival collections). Nor does there appear to be a detailed historical assessment of how the Mississippi River delta has been compared with other deltas around the world.

- **Preparation of a Mississippi River Delta Research Synthesis report offers a research opportunity for the Water Institute. This report could include an institutional map of major research institutions and programs. It would require a robust geographic definition of the delta, a historical review of Mississippi River delta research and development, and a perspective on the international context for research.**

Condition of the Delta Assessment

An important requirement for better understanding and forecasting the effects of interventions (both physical actions and policies) on a system as large and complex as the lower Mississippi River delta is to establish some type of robust baseline for comparison. A research synthesis of the sort described above would indicate strengths and gaps in current knowledge. A baseline assessment ideally would fill those gaps to provide a comprehensive dataset of the state of the complex human-environmental system time that can be considered a "snapshot" of the system.

This type of assessment could also serve as a valuable scientific planning method. For example, future "without action" scenarios could be constructed to forecast how changes in the baseline may change over time, which in turn could provide a basis for forecasting effects of future interventions. The State of Louisiana's 2012 Coastal Master Plan (Master Plan) includes data and analyses that were used to build baselines and future "without action" scenarios. These could be reviewed to ensure that they have similar spatial and temporal features, and to identify opportunities to expand data collection and related analyses.

- **A comprehensive state-of-the-delta baseline for data across water, landscape, and human factors has not been established. As such, this is a research gap and a research opportunity for the Water Institute and allied organizations.**
- **The Water Institute could provide the central motivation and coordinating effort for the promising research opportunity of developing a "condition of the delta" assessment. This ideally would be conducted with broad collaboration among stakeholders and scientists working in the delta.**

Research Design for Diversions

The Louisiana 2012 Coastal Master Plan identifies many possible diversions of flows and sediment from the mainstem Mississippi River as a means to promote wetlands restoration. From antiquity to early modern times, there have been advocates for and experiments with overbank flood methods in China, India, and Europe. The Louisiana 2012 Coastal Master Plan proposes restoration projects of historical significance.

The hydrologic, geomorphic (sediment), ecologic, and socioeconomic outcomes from these diversions will have uncertainties even as projects proceed. These diversions offer the Institute an excellent opportunity to design experiments as part of the diversion projects. Results from these experiments would likely help reduce uncertainties, enable science-based adjustments of initial diversions, and help design future diversions. Such experiments could offer opportunities to collaborate on investigations with regional scientists and other experts from the federal government, Louisiana state government, regional universities, and international scientific organizations.

An active adaptive management framework and process would help organize and guide these processes. The theory and practice of adaptive management have been interpreted and implemented in different ways. Adaptive management can take a more formal (active) form that includes model(s) and hypotheses for explicit experimentation and testing, or less formal (passive) forms. Most experts and practitioners would consider any form of adaptive management to reflect a paradigm of "learning while doing." For purposes of this report, adaptive management involves monitoring and evaluation of outcomes from management actions that have considerable uncertainties, and subsequent adjustments and learning based on those evaluations.

The Water Institute already has engaged in some aspects of proposed diversion studies with the Louisiana Coastal Protection and Restoration Authority (CPRA). Additionally, it may be expected that extreme events and ecological surprises will occur during implementation of restoration projects, which will require rapid research responses to understand their immediate effects and collect perishable data. Similar future research opportunities for the Water Institute will entail further collaboration and agreements with the Louisiana CPRA.

- **The Water Institute could identify key decision-relevant scientific uncertainties in planned diversion projects, propose building experiments into project and policy design, and contribute to scientific monitoring of results.**
- **Design of scientific research to support adaptive management of large-scale ecosystem restoration projects is a significant research opportunity in the Mississippi River delta context.**
- **As some uncertainties will unfold during the course of diversion experiments, a "quick response" research grant program for internal and external applicants could facilitate rapid collection of perishable data in the event of environmental surprises and hazards.**

Long-Term Monitoring Opportunities

Long-term monitoring traditionally is conducted by government agencies. Data collection on demographics, land use, economic activity, weather, rainfall, streamflow, tides, and water quality variables are well-established, and largely uncontroversial, tasks of government because of their recognized societal value. However, in a budget-constrained setting, commitments to long-term environmental monitoring may be reduced in some aspects and expanded in others; for example, remote sensing and citizen-science monitoring may expand new information and communication technologies.

- **A research opportunity in complex deltaic systems is to help identify emerging decision-relevant variables and time scales, and then to propose cost-effective adjustments in monitoring programs, including new data sources, methods, and technologies.**

Human Settlement and Occupation

In the context of water management decisions and policy, related land use processes have often been overlooked or underappreciated in planning decisions and processes, in part because of their political dimensions and other challenges. Yet it is essential that social processes and policies that influence land use change be included within the scope of research for truly integrated water and environmental management.

- **There are research opportunities in the lower Mississippi River delta for analyzing land use and settlement patterns and trends, and for explaining how projects and policies influence those trends in ways that advance or constrain the paths and prospects for integrated water and environmental management.**

Tectonics and Deltaic Zonation

Tectonic processes exert a major control on delta stability in the Mississippi River Delta. Since 1930, over 600 square miles of land area south of the Golden Meadows fault zone has been converted into open water habitat by slumping. Although precise fault alignments are not always clear, much of the region south of this fault zone is unstable, and land loss rates continue at a particularly rapid pace. Oil and gas and groundwater extraction contribute to land loss in this area, but tectonic structure and dynamics are the primary geophysical drivers, and as such, it is critical that tectonic stability considerations be integrated into regional water and environmental management processes.

- **More detailed mapping of major geologic areas of relative stability, major land loss vulnerability, and land building potential could help guide research on diversions and coastal protection project performance.**

SCIENCE-POLICY ANALYSIS: AN EMERGING RESEARCH FRONTIER

Key challenges for integrated water and environmental management include the articulation of salient research questions in a given lower river/delta system. These questions span a broad range of science and related policy disciplines and include hydrology, ecology, socioeconomic trends, policies, and governance issues; as well as the relationships, linkages, and potential trade-offs among them. Science-policy analysis, as discussed in this report, refers to at least three related lines of research. The first is scientific research in support of public policy analysis and deliberation, which is addressed throughout this report. The second involves scientific analysis of environmental policy alternatives, which is discussed in Chapter 3. A third line of research seeks clearer understanding of how scientific research is used effectively in policy processes, including topics such as decision support systems and adaptive management, which are discussed in Chapter 4.

Some deltaic regions and nations, notably the Netherlands, have undertaken a broad range of formal science-policy studies that provide partial analogues for research in the Mississippi River delta.

- **There is a growing body of international research on science-policy studies of deltaic vulnerability and sustainability. At the same time, there are expanding opportunities for rigorous comparative research on science-policy programs in other regions, such as the Netherlands, for integrated water and environmental management in the Mississippi River delta.**

Science-Policy Research and the Louisiana Coastal Master Plan

New infusion of funding will support Mississippi River diversions and associated (re)construction of wetlands and barrier island protection, as envisioned in the Louisiana 2012 Coastal Master Plan. These restoration plans, and associated adjustments in economic activities and human settlement, provide unique learning opportunities of global and local significance for planning and designing "soft" ecological engineering and design at the coastal margins, and for integration with "hard" engineering infrastructure and policy. Interactions among multiple projects and policies present complex scientific challenges.

- **There is an excellent opportunity for the Water Institute to build a research program around multiple interacting types of restoration projects and policies.**

- **There are also near- and medium-term research opportunities on the integration of storm protection structures with delta restoration projects that emphasize natural or green infrastructure. This integrated approach to research could encompass and contribute to the objectives of a vigorous energy and marine transportation economy, storm risk reduction, commercial fisheries, recreational opportunities, and a healthy coastal ecosystem.**

Collaborative Modeling, Negotiation, and Conflict Resolution

The scientific investigations, public meetings, and outreach that supported the Louisiana 2012 Coastal Master Plan were an impressive effort to move toward integrated water and environmental management. The Master Plan process engaged stakeholders through public hearings and workshop discussions. However, some stakeholders may not have been as fully or creatively engaged as possible in analytical modeling that led to recommendations, which may contribute to some controversies regarding Master Plan proposals. Integrated water and environmental management processes often entail collaborative modeling, negotiation theory, and conflict resolution experiments.

- **The Water Institute would have an excellent opportunity to promote, and lead, more advanced scientific stakeholder engagement in joint fact finding and modeling processes. A strong contribution to research on negotiation and collaborative modeling would entail some level of commitment by the Water Institute to developing the required professional skills to create and lead collaborative modeling procedures.**

Citizen Science

The concept of "citizen science" involves participation and collaboration of members of the general public in scientific research, often as unpaid volunteers and in education programs. Such participatory efforts serve to engage and educate the public about local and regional scientific issues. Supporting and promoting active input and dialogue with citizens in the region about hurricane protection, settlement and land use issues, and ecosystem restoration is an activity where modest investment could provide many benefits.

- **The design of collaborative processes that mobilize members of the public to facilitate monitoring programs is another research opportunity for the Water Institute. Part of this effort could include**

a leadership role for the Water Institute in developing digital information and communications technology with citizens in the lower Mississippi River delta.

- **Hosting of international citizen-science workshops also could identify innovations in other deltas that have relevance for the lower Mississippi, and ultimately help transfer knowledge to those regions.**

Developing Decision Support System Tools

As indicated in the observations above, the delta faces complex decision-making problems characterized by uncertainties about alternatives, scenarios, and trade-offs among water and environmental uses. However, it also has an expanding range of creative approaches for addressing them. The Louisiana 2012 Coastal Master Plan took an important step toward addressing these types of issues through its Planning Tool. Restoration project implementation will entail broader analyses, and effective interdisciplinary communication of, complex engineering, socioeconomic, and environmental scenarios, impacts, and trade-offs. Broader analysis of these structural, nonstructural, policy, and ecological restoration alternatives would likely benefit from development of additional decision support system tools.

- **Development of decision support system applications represents another science-policy research opportunity. This work initially could help support restoration project implementation, encourage integration of structural and nonstructural water and environmental management alternatives, and also encourage participatory stakeholder and citizen-science programs.**

RESEARCH COORDINATION AND ORGANIZATIONAL OPTIONS

Research Coordination

There are highly ranked universities and research laboratories conducting research in the Mississippi River delta, including Louisiana State University, Tulane University, University of New Orleans, and University of Louisiana at Lafayette. There also are federal agencies in Louisiana and the region, notably the U.S. Army Corps of Engineers and the U.S. Geological Survey, that have decades of experience in and extensive knowledge of the region, and support research programs in fields of interest to the Water Institute, such as hydrodynamic modeling and ecological restoration.

Cooperation among institutions on integrated water and environmental research has not always been as strong as might be hoped. Similarly, despite the depth of expertise in deltaic science among the industries that operate here—notably oil and gas industries, fishing, navigation, salt mining, dredging, construction, and tourism—some industry data and expertise have not been fully available to support research to address broad human-environmental needs.

- **The Water Institute will have opportunities to build working, collaborative relationships with a rich variety of research and educational institutes, and private industry—including energy exploration and development firms, fisheries, tourism, and the maritime transportation sector. Examples of these opportunities include hosting international seminars, scholar exchange, establishment of a special delta research journal, and insurance for laboratory facilities or research equipment.**

Institute Organizational Options

As a new research entity, the Water Institute has an unusual opportunity to develop a research scope and agenda, organizational structure, and mode of operation unencumbered by historical constraints. As it is not part of a university or government agency, the Water Institute will require a distinctive type of organizational structure. Strategic factors to be considered by Water Institute leadership include mode of operation, incentives and expectations for staff, mechanisms for prioritization of work, optimization of competencies, and efficient organizational structure.

COMPARATIVE RESEARCH: TRANSFERRING AND APPLYING KNOWLEDGE

The Water Institute's intent to engage in comparative international research holds much promise for improving strategic research and decisions both on the lower Mississippi and in other delta regions. Although no two complex deltas are strictly comparable, analysis of similarities and differences in research measurements, methods, and management issues can be useful. It was not possible or necessary within the scope of this study to list and describe in detail the delta systems that may be relevant to the lower Mississippi River. However, traits of the Mississippi River delta that merit or suggest comparison include hydrologic dynamics, sediment transport, economic activities, environmental hazards, management institutions, and other agents of change.

As it is developing its research programs and expertise, the Water Institute may selectively establish international research linkages with lower river/delta regions, such as with other delta regions where collaboration seems most feasible and pertinent to the Mississippi River delta. To enhance credibility both in the region and abroad, the Water Institute may focus on building its scientific capacity in the lower Mississippi River delta, in part through strategic and focused international research.

One possibility for the Water Institute is to initially focus some of its international initiatives on inviting scientists from around the world to visit and collaborate in research activities in the lower Mississippi River delta. Building collaborative, international relationships by this means, and addressing local scientific issues, may also place it in a strong position to productively engage in research opportunities in other parts of the world. Several principles can help guide development of sustainable international scientific relationships.

- **The Water Institute could define those traits that best characterize the Mississippi River delta, and begin to establish connections and comparisons with a small, diverse set of other delta regions. The Water Institute subsequently could branch out from there, as interests and staff resources permit.**
- **To help prioritize its own international studies and its collaborations with other delta regions, the Water Institute could develop and employ a simple framework of international research *aims* and *methods* to screen, rank, and select its international activities.**

The timing of international studies also is relevant. A broad suite of interbasin comparisons could be developed over the medium to longer term, in each case building upon core research programs in the Water Institute. A good example is the 2010 study of vulnerability and sustainability of ten deltas conducted by the Delta Alliance, a collaborative international knowledge network.

- **In the near term, a small set of strategic Gulf-centric deltaic comparisons may be the main type of international research on analogies that the Water Institute undertakes.**
- **Over the medium term, Water Institute scientists would benefit from strategic engagement in multidelta comparisons, such as the Delta Alliance's study of vulnerability and resilience.**
- **In the longer term, depending upon its Mississippi River priorities and expertise, the Water Institute may be in a position to develop a small number of continuous, cooperative problem-driven and thematic research programs with other delta regions.**

Examples include (1) environmental/ecosystem restoration—Rhine, Danube, Irrawaddy; (2) natural hazards mitigation—Ganges-Brahmaputra and Mekong; (3) energy industry, environment, and conflict—Niger, Yellow River, Indian Ocean, Arctic deltas; (4) sediment trapping and land loss—Mekong and Yellow; and (5) urban planning and flood risk reduction—in New Orleans, the Connecting Delta Cities program, and Pearl and Yangtze deltas.

1

Introduction

The first years of the twenty-first century witnessed increasing concern about the sustainability of deltaic environments in the United States and internationally, which included escalating calls for research, restoration, and improved water and environmental management (Day et al., 2007; Foufoula-Georgiou et al., 2011; Galloway, et al., 2009; Giosan and Bhattacharya, 2005; Paola et al., 2011; Syvitski, 2009; Vörösmarty et al., 2009). Louisiana research scientists and universities have pursued these issues for decades, internationally as well as in the Mississippi, as have other major deltaic research institutions around the world, particularly in the Netherlands. International scientific communities have organized deltaic research consortia, including the International Geosphere Biosphere Program (IGBP); Land-Ocean Interactions in the Coastal Zone (LOICZ) program (Overeem and Syvitski, 2009); the Delta Alliance; the Connecting Delta Cities program; DeltaNet; ESPA Deltas; and the USGS DRAGON program (2013). Hurricanes Katrina and Rita; tropical cyclones Aila, Nargis, and Sidr; and tsunami-driven coastal flooding have catalyzed regional, national, and international inquiry. The 2010 Deepwater Horizon explosion and oil spill in the Gulf of Mexico compounded these hazards and required massive cleanup and restoration programs. Chapter 2 addresses this array of problems and challenges.

In the wake of these events, the Water Institute of the Gulf (referred to as the Water Institute in this report) was incorporated in 2011 and began its operations in 2012. Located in Baton Rouge, the Water Institute was established as an independent scientific advisory body. Its establishment follows a precedent set by the Deltares Research Institute in Delft, Netherlands. Initial financial support was provided through a grant from the Baton Rouge Area Foundation and contracts with the State of Louisiana. The mission of the Water Institute is described as follows:

> . . . provide the state of Louisiana with a central point of science and engineering capacity, one that can help the state build better projects more quickly. By serving as a vehicle for collaboration among the best scientists and engineers in the world, The Water Institute will drive innovation in coastal restoration and hurricane protection, building world class expertise in these areas. This expanded capacity will not just inform federal and state efforts in Louisiana, it will eventually create a center of science and engineering excellence that can serve communities throughout the Gulf Coast and beyond.
>
> (The Water Institute, 2013a)

The Water Institute's initial scope of work is largely defined by and intended to serve the Louisiana Coastal Protection and Restoration Authority (CPRA). Its early studies include critical review and feedback of the first phase of proposed diversion for marsh restoration projects (Reed, 2013). In its initial year of operations, the Water Institute established four main scientific branches and hired senior scientists for each of these programmatic branches (The Water Institute, 2013b). The Water Institute's next round of staffing will focus on a cadre of junior research scientists capable of serving as co-principal investigators and project managers.

This report offers advice to the Water Institute that it might use as part of its strategic planning process. The NRC and the Water Institute agreed upon a scope of work that focuses on strategic research to support integrated water resources management in the lower Mississippi River delta and includes international comparative assessments (Box 1-1). This report promotes a human and environmental systems approach to scientific research that supports integrated water and environmental resources management in the lower Mississippi River and delta (Figure 1-1), and offers ideas regarding comparative assessments with other, relevant deltaic regions around the world (Figure 1-2).

This report's statement of task requests the NRC committee to offer advice for setting research priorities to support integrated water resources management in lower river and deltaic systems. The report thus has a strong science research program emphasis. Much of the advice herein is based upon the committee's collective expert judgment, and not necessarily detailed review of specific bodies of science, or testing of hypotheses. Research directions thus are presented in the form of promising alternatives and opportunities open to the Water Institute, as opposed to conclusive or definitive science-based recommendations and organizational imperatives.

BOX 1-1
Statement of Task

An ad hoc committee of the National Research Council (NRC) will provide independent advice on strategic research to support integrated water resources management to the Water Institute of the Gulf—a nonprofit, independent research organization located in Baton Rouge, Louisiana. The Institute's focus is on the lower Mississippi River and its delta and coastal region, but it also will draw upon ideas, technologies, and solutions from around the world in addressing local problems, and to export knowledge to address water management issues in deltaic and coastal systems globally. The Institute plans to conduct integrated research that explores linkages among natural science, engineering, and the dynamics of social and economic systems that underpin water management decisions. The Institute considers Integrated Water Resources Management (IWRM) to reflect these multidisciplinary factors.

In advising the Institute, the NRC committee will consider several issues that fall into three topical areas: (1) common problems and challenges, (2) strategic research, and (3) transferring and applying knowledge.

Common Problems and Challenges

- Discuss other prominent large deltaic and coastal systems focusing on why and how they may be analogous to and relevant to scientific issues and management decisions in the lower Mississippi River and delta system.
- Identify key challenges for IWRM in large deltaic systems in general, and types of research that can contribute to meeting these challenges.
- Discuss prominent lessons and promising IWRM practices from large river delta systems, including the lower Mississippi River, that can be applied broadly.

Strategic Research for IWRM

- Identify unmet research needs in the lower Mississippi River and its delta complex, and in large river/delta/coastal areas outside North America, for which opportunities exist for research to gain understanding necessary to further IWRM.
- Discuss promising approaches, including organizational structures and related processes, for identifying and integrating relevant multidisciplinary knowledge and skills into management decisions for large deltaic regions.

Transferring and Applying Knowledge

- How can the Institute utilize knowledge gained from the lower Mississippi River and delta system in developing a research program to support water management decisions in other large river/delta complexes?

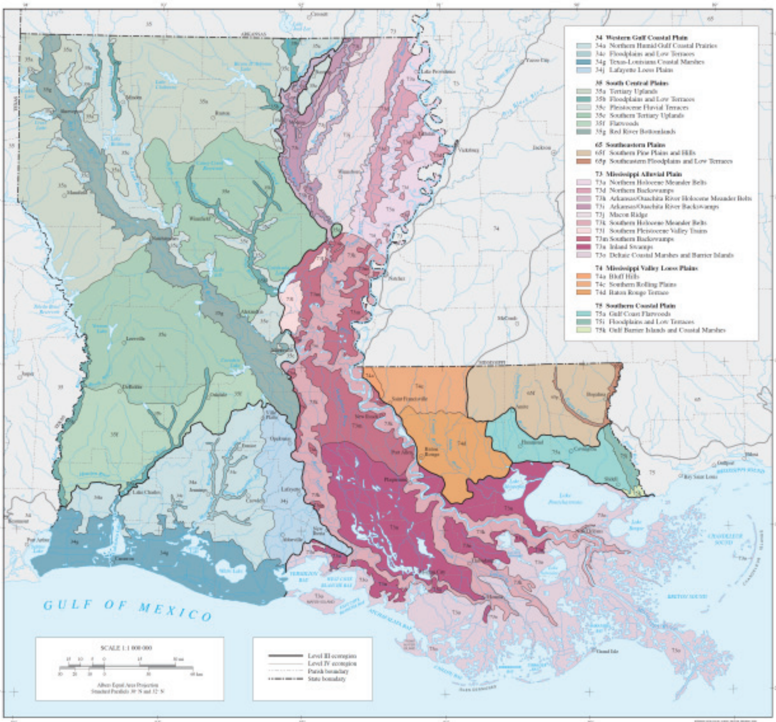

FIGURE 1-1 Louisiana Level IV Ecoregions.
SOURCE: EPA, 2006.

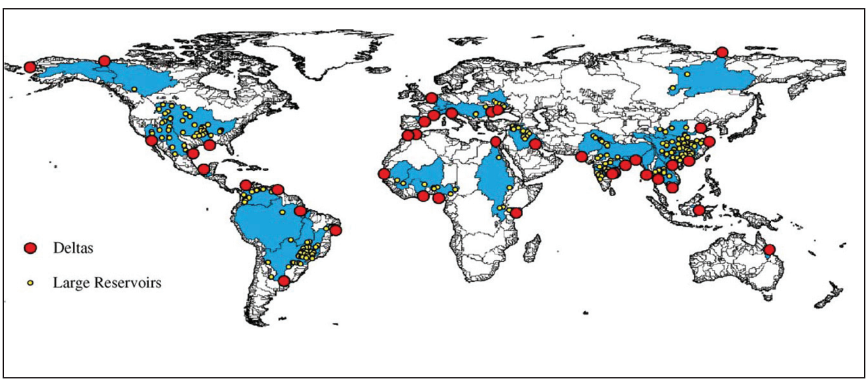

FIGURE 1-2 Major international deltas and their river basins.
SOURCE: Ericson, Vörösmarty et al., 2006.

This report does not identify priorities among these many opportunities, but the final chapter provides comments regarding a process for prioritization.

INTEGRATED WATER RESOURCES AND ENVIRONMENTAL MANAGEMENT

The concept of "integrated water resources management" (IWRM) features prominently in this report's statement of task, and has been an important initial theme for the Water Institute. Although there is a vast literature on this subject, there is no single definition of the concept, or commonly idealized model of its implementation. In general, however, it describes a systematic approach to managing water and related environmental resources, which considers natural systems, socioeconomic conditions, and institutions and governance structures.

Integrated water management has existed in various forms for many decades, describing aspects of water management programs and activities around the world. The actual practices of integrated water management have ancient origins, as early societies sought to attain good quality water supplies in sufficient quantity, safety from water-related hazards, and low cost waste disposal (Angelakis et al., 2012; Mithen, 2012; Tvedt, 2006-2013). Modern industrialization in both rural and urbanizing regions brought advances in water development, often of a specialized yet fragmented nature, which led to calls in many periods for more integrated water management. Dating from at least the turn of the last century, integrated water management has referred to progressively more comprehensive approaches to solving problems involving water.

In the United States, Progressive Era watershed and river basin studies in the late nineteenth and early twentieth centuries marked the advent of integrated planning (Wescoat, 2000). The Tennessee Valley Authority (TVA), and its multiple missions of flood control, navigation, power generation and rural electrification, soil conservation, and community planning represented a milestone and major advance in integrated water resources management. In its early river basin manifestations by the U.S. Army Corps of Engineers and others, integrated water resources management had a strong engineering dimension, which was reflected in river systems that featured large-scale engineering works with multiple objectives (White, 1957), principally for reducing flood peaks, storing water, and generating hydroelectric power. Smaller reservoirs, along with soil and water conservation planning, were emphasized at the watershed scale. Over time, there has been a broadening of the concept at both of these scales to include ecological change, social and economic systems, as well as institutions and policies for water governance. Mitchell (1990) has compiled diverse examples of integrated water management in various regions of the world that provide further background.

The late geographer Gilbert F. White reflected on the 50-year record of integrated water management, citing the need to (1) continue to expand the range of choice among management measures; (2) deepen the quality of criteria to evaluate those management measures; and (3) conduct rigorous post audits of completed projects to determine what has actually happened, as compared with what was planned (White, 1998). In more recent years, the U.S. Army Corps of Engineers has developed formal curricula for IWRM to address these issues, underscoring that IWRM is (1) a process, not a goal, (2) a process directed toward multiple goals, and (3) an incremental rather than comprehensive process (Cardwell et al., 2006). The Corps emphasizes integration of objectives, institutions, and different spatial and temporal scales (ibid.). Another recent study has compared coastal zone management with IWRM (Thompson, 2012). These emphases go beyond earlier watershed and river basin frameworks for integrated management.

In international practice, by comparison, IWRM has a different history, meaning, and record. Biswas (2008) dates international usage of the IWRM concept at least back to the Mar del Plata water conference of 1977. IWRM was adopted as a planning approach by the Global Water Partnership (2000, p. 22), which formally defined it as "a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." After two decades of experimentation, a significant body of criticism has developed which asserts that IWRM is too comprehensive, rarely implemented, and insufficiently attentive to the political dimensions of water management (Beveridge and Monsees, 2012; Biswas, 2008; Mollinga et al., 2006; Orlove and Caton, 2010).

However, others rebut some of these criticisms with examples of implementation in Canada (Mitchell, 2006), a mix of U.S. and international projects and practices (Lenton and Muller, 2009; and a recent country survey by U.N. Water, 2012). Some European nations, including the Netherlands, employ IWRM frameworks for analysis and planning. Clearly, the "IWRM" concept has a wide range of region-specific definitions, interpretations, and manifestations.

In light of these debates about IWRM, per se, this report chose to move away from the acronym and acrimony, and focus on IWRM selectively where it has important insights to offer. This report otherwise uses the phrase "integrated water and environmental management" in lower case, as ordinary language for approaches that strive to link social, environmental, and institutional processes through a systems approach. This general concept of integrated water and environmental management is briefly introduced below, and elaborated upon in Chapter 4.

In the United States, numerous water management entities and stakeholder groups periodically convene discussions among water users to share their respective concerns and consider cross-sector relations, as well as possible compromises and operational changes. The U.S. Army Corps of Engineers routinely seeks to integrate and balance multiple water sectors in the operations of its hundreds of dams across the United States. Along the Missouri River, for example, the Corps is authorized to operate its mainstem reservoirs to serve flood control, irrigation, municipal and industrial water supply, navigation, and hydroelectric power generation, and to provide benefits to recreation, fish, and wildlife (see NRC, 2002).

Along the Colorado River in the arid southwestern United States, the U.S. Bureau of Reclamation operates its large storage dams—Glen Canyon and Hoover dams—to achieve and balance goals and purposes of hydroelectric power generation, water delivery obligations, tribal trust duties, and ecological values including endangered species protection, recreation, and navigation.

Other examples across the nation abound. The Ohio River Sanitation Commission (ORSANCO) is an interstate body with water quality responsibilities along the Ohio River, and the Upper Mississippi River Basin Association (UMRBA) is a five-state entity that convenes discussions and sponsors studies of numerous water-related issues of broad importance to many users in the upper Mississippi River basin. The Delaware River basin has been managed by a unique federal-state river basin commission since 1961 to promote regional economic development, protect the environment, and improve community quality of life. The commission has undertaken a goal-based watershed management approach, in which alternative water uses and discharges are assessed in terms of both socioeconomic and environmental impacts (Collier, 2004).

There also are groups that convene a wide array of stakeholders to facilitate discussion and promote collaboration. Examples include the Adaptive Management Work Group in the Colorado River Basin, the Missouri River Recovery and Implementation Committee for the Missouri River, and the Apalachicola-Chattahoochee-Flint (ACF) stakeholders group. Each of these entities includes dozens of different stakeholders to better integrate multiple perspectives into decision making. There are less formal entities that convene occasional meetings of different state agencies, or user groups, to facilitate communications. These include the Colorado River Water Users Association, and the Lower Mississippi River Conservation Committee.

U.S. federal and state water managers aim to improve integration of water and environmental decisions across water sectors, and work closely with scientific research agencies, and others, to identify and use information regarding water resources conditions and trends. Examples of these scientific agencies are, at the federal level, the U.S. Fish and Wildlife Service and the U.S. Geological Survey, and at the state level, state natural resources agencies. In some instances, multiple-stakeholder programs have been established by federal and state governments. One example is the Grand Canyon Monitoring and Research Center (GCMRC), a Department of the Interior scientific body in Flagstaff, Arizona, that works collaboratively with the Adaptive Management Work Group in several ecosystem monitoring programs, including habitat conditions for federally listed species. On the upper Mississippi River, UMRBA reports on water quality and environmental conditions are informed via input from many federal agencies (e.g., Upper Midwest Environmental Sciences Center; U.S. Geological Survey), and state natural resource agencies from Illinois, Iowa, Minnesota, Missouri, and Wisconsin. Scientific information that is used within settings of shared water resources systems across the United States takes many forms and includes water quality monitoring data, assessments of endangered species and habitat needs, decision support systems (DSS) that model reservoir operations and alternative management regimes, and activities such as "Shared Vision" modeling, which involves stakeholders in the formulation and analysis of management alternatives. Scientific information and research are standard components and input to many collaborative efforts in the United States aimed at better integration across multiple water users.

A major theme of this report is ways in which scientific research can provide information to more systematically integrate water and environmental management across various sectors. In the lower Mississippi River and delta region, the primary water sectors include navigation, flood mitigation, hurricane protection, water supply, fisheries, and ecosystems management. The report identifies opportunities to obtain better information on natural, social, economic, and governance dimensions of water and related resources, their relations and connections, and shows how that information can be used in management decisions. It builds on extensive work and applications in integrated water resources management, and considers the concept in a broad sense to include natural systems, social and economic processes, and institutions and policies for water governance. It employs the phrase "integrated water and environmental management" to refer to interdisciplinary, science-based efforts at better cross-sector integration.

DEFINING THE DELTA

There is no single definition of the lower Mississippi River and its delta. In the largest sense, the lower Mississippi River extends as far north as Cairo, Illinois, and the confluence of the Ohio and Mississippi Rivers, which at one time was coincident with the Corps of Engineers' (former)

Lower Mississippi Valley Division. Alternatively, the lower Mississippi extends northward roughly to Vicksburg, Mississippi, and includes portions of the Corps' New Orleans and Vicksburg district offices. At the narrowest end of the spectrum, some inventories limit the delta to the current "bird's foot" distributary in the northern Gulf of Mexico. This report adopts a working definition in between these extremes that includes the apex and northernmost point of the Mississippi River delta at the Old River Control Structure, including the Atchafalaya River valley and part of the Chenier plain to the southwest and south, and the margin of the southern coastal plain to the southeast.

Within this context, this report concentrates on the lower Mississippi River deltaic and coastal areas. More complete integration of lower river and delta will require some attention to the division of Mississippi River flows at the Old River control structure, which is an important feature in the Corps of Engineers' Mississippi River and Tributary (MR & T) project water control infrastructure (see Figure 1-3; see p. 39 for further discussion of the MR & T project).

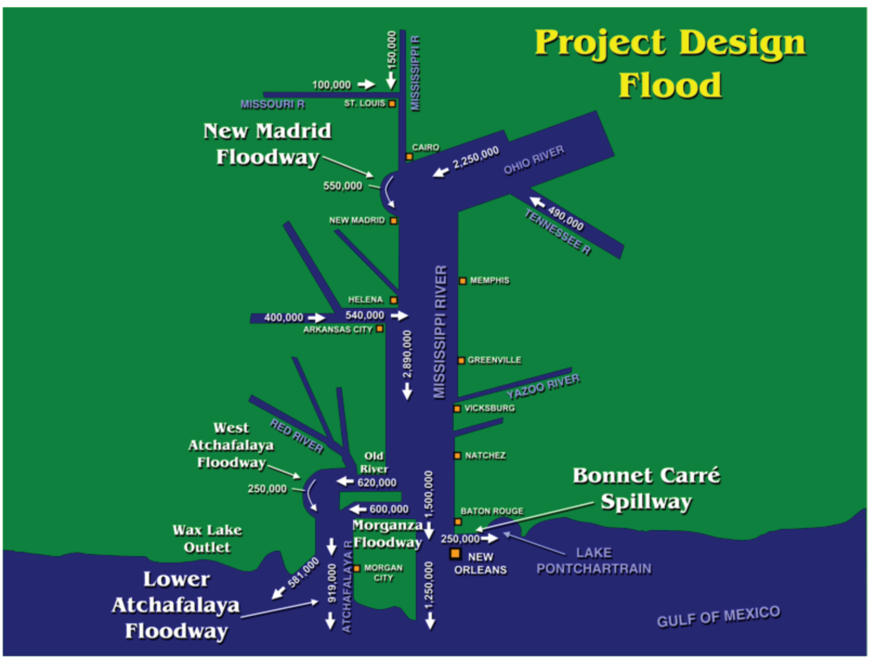

FIGURE 1-3 Mississippi River and Tributary project water control infrastructure.
SOURCE: USACE, 2011.

TIMING OF STRATEGIC RESEARCH OPPORTUNITIES FOR THE WATER INSITUTE

Understanding water and environmental issues in the Mississippi River delta requires consideration of time scales associated with major agents of change. Geological and evolutionary timescales of tens of thousands of years drive some processes, which set the stage for conditions largely beyond human control. Other agents of change work on diurnal or shorter scales, where human interventions can have effects (both positive and negative). Integrated water and environmental management must draw upon this full range of environmental timescales and translate them into meaningful interpretations for human time scales, which themselves are a matter for focused deliberation. The question of time-scales is critical for future economic and ecological development of the Mississippi delta. Infrastructure, land use, and management decisions can have implications for decades to centuries. The human dimensions of time scales are encapsulated in the issue of floodplain development. Some floodplain residents, for example, may be comfortable living in a 100-year flood plain, as a 1 percent per annum risk of flood may seem acceptable. Others may have little economic choice. It is not widely appreciated that the 100-year flood plain has an approximately 26 percent chance of flooding during a typical 30-year home mortgage. Louisiana has one of the highest concentrations of multigenerational populations in the United States, so decisions made based on short-term considerations can have reverberations through generations of a family.

For science-policy relevance, this report adopts the three rough time scales of the near term, medium term, and longer term. The near term refers to the interannual time scale of one to five years. The medium time scale refers to five to twenty years, that is, the interval between master plans into the foreseeable planning future. The longer time scale refers to the multi-decadal periods of human generations, such as 100- to 500-year flood protection. As an early point of comparison, the Dutch coastal protection system has a history of approximately 1,000 years, and it plans for 1 in 10,000 year extreme events (Deltacommissie, 2008; Verduijn et al., 2012).[1]

REPORT AIMS, STRUCTURE, AND AUDIENCE

In addressing the points and questions identified in the statement of task, this report aims to promote systematic, science-based management of water and related resources across multiple sectors. This systems-level per-

[1] Such discussions of flood and storm return intervals assume that frequencies and magnitudes do not change due to nonstationary climate processes. Such assumptions, however, fall under careful scrutiny under paradigms of nonstationarity (see Milly et al., 2008).

spective is consistent with the notion of integrated water management that is an important theme in the Water Institute's developing research program.

Another prominent theme in this report's statement of task is comparisons, commonalities, and knowledge transfers between the lower Mississippi River delta and other lower river and deltaic regions around the world. Comparative assessments between the lower Mississippi River and other lower river regions present both challenges and opportunities. At one level, the history, hydrology, engineering structures, and other features of the lower Mississippi River region are unique. At the same time, there are common features and management challenges in many lower river/delta systems, including sediment management, salinity intrusion, floods, and other environmental hazards. These commonalities present opportunities to share experiences and expertise, and to learn from management actions in other regions. This report explores in greater detail the prospects for comparison and knowledge transfer between the lower Mississippi River and other deltas, and offers some thoughts on structuring comparative assessments.

The report is divided into six chapters. Chapter 2, "Lower River and Deltaic Systems:Common Problems and Challenges" corresponds with the first section in the statement of task (Common Problems and Challenges). Chapters 3 through 5 address the points and questions in the statement of task's second main section (Strategic Research for IWRM). Chapter 6, "Comparative International Deltaic Research: Transferring and Applying Knowledge" addresses the points in the statement of task's third major section.

In addition to the chapters on strategic scientific research, science-policy research, research coordination and organization, and transfer and application of research results (Chapters 3-6), three other themes are cross-cutting through the report: (1) the systems approach to water and environmental research in the lower Mississippi River and delta; (2) the prominence of commercial activities broadly defined—from fisheries to petrochemical exploration and refining, from commercial navigation to tourism—and the importance of engaging these stakeholders in water and environmental deliberation; and (3) comparisons and contrasts with other lower river and delta systems around the world.

Like most National Research Council reports, this report's intended audience is broad. In addition to the Water Institute, the report likely will be of interest to the State of Louisiana and especially its Coastal Protection and Restoration Authority, author of Louisiana's 2012 Coastal Master Plan (Master Plan). Stakeholders and industries in the region also may find the report of interest. These groups include petrochemical development industries, commercial navigation, and fisheries. Nongovernmental organizations with missions related to ecosystem protection and restoration also should find it of interest, as may local communities in the lower Mississippi

River delta and across coastal Louisiana. Federal agencies with water and environmental management, and scientific, missions also should find it of interest. These agencies include the National Oceanic and Atmospheric Administration, the U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, and the U.S. Geological Survey. International water researchers and organizations such as the International Geosphere Biosphere Project Land-Ocean Interactions in the Coastal Zone (LOICZ), Delta Alliance, and Connecting Delta Cities networks, from which the report has benefited, also may find it useful.

This report was produced on a timeline of roughly six months from the committee's first meeting to the report's issue following external peer review. The committee held its first meeting in Baton Rouge in April 2013, and its second meeting in Washington in early June 2013. The committee's April 2013 meeting featured numerous guest speakers; the committee's June 2013 meeting was held mainly in closed session during which the committee worked on its draft report (a full list of invited speakers at these two meetings is presented in Appendix A).

2

Lower River and Deltaic Systems: Common Problems and Challenges

The Water Institute of the Gulf intends to serve as a source of shared knowledge about lower Mississippi River and delta issues, and to accumulate knowledge about water and environmental management around the world, particularly as it relates to strategic research on the lower Mississippi river delta. The first portion of this report's statement of task is the topic of "common challenges and problems." This chapter identifies common issues in the Mississippi River delta and analogous lower river delta systems.

A PERSPECTIVE ON THE MISSISSIPPI RIVER DELTA

Water, Land, and Ecosystem Dynamics

Deltas form where rivers intersect the sea, disperse laterally, and deposit sediment, often in a classic triangular delta (Δ) pattern. Sediment deposition results from decreases in flow velocity, which diminishes the ability of the fluid to transport sediment. Delta ecosystems comprise interlinked networks of river channels, bayous, tidal creeks, wetlands, and sand/gravel bars, which continuously evolve through the collective forcing of river flow, waves, tides, sediment deposition, and human infrastructure. Delta habitats, particularly saltmarsh wetlands and associated coastal waters, are highly productive, supporting fisheries and extensive biodiversity along with a range of valuable ecosystem services. Delta ecosystems are, however, fragile environments that respond rapidly and markedly to changes in environmental conditions (Syvitski et al., 2009). A delta is formed, maintains itself, and either grows or retreats through an interplay between time and space scales of water flow, sediment supply, ecosystem adaptation, geologic change, weather events, and variations in climate.

River deltas comprise roughly five percent of global land area and are home to more than 500 million people (Overeem and Syvitski, 2009). Changing environmental conditions and intensive development within these areas represent significant challenges to delta stability (Overeem and Syvitski, 2009). Poorly planned development can affect the self-organizing abilities of these ecosystems (Bianchi and Allison, 2009), thereby limiting adaptation to ongoing changes, which ultimately may affect future economic and development potential.

River deltas are formed by successive bifurcation (separation) of river channels, which occurs near a river's mouth and as the slope of the landscape becomes shallower. Development of bifurcations can occur either gradually—through slow processes of sediment deposition and bank erosion—or rapidly, through flooding events with major avulsive action. Sediment supply and erosive forces (heightened by flooding) thus are a delta's principal geomorphic forces. An example of bifurcation in the Mississippi is the junction with the Atchafalaya River, a primary distributary that now diverts roughly 30 percent of the flow of the Mississippi. The Atchafalaya delta currently is one of the few areas along the Louisiana coast that is gaining ground and extending seaward (progradation). The increase/decrease of any delta is determined by the balance of sediment supply and erosive forcing against the background geologic time scales of landscape lifting/subsidence, and increases or decreases in sea level.

Upstream impoundment of rivers as well as dike and/or canal construction decrease the river's sediment load (Ericson, Vörösmarty et al., 2006), which tends to decrease a delta's area when upstream sediment supply is critical to balance forces that otherwise cause the delta to sink or erode, such as subsidence of wetlands (Meade and Moody, 2010). Groundwater and resource extraction (e.g., mineral, oil, or gas) can accelerate landscape subsidence, making delta habitats susceptible to erosive forces from sea level rise, storm surge, and wave action. Tectonic processes provide a background forcing on the Mississippi Delta; fault-driven slumping over geologic time scales combined with the severe reduction in the historic sediment loading from the Missouri River contributes to loss of land and habitat (Dokka et al., 2006). The loss of wetland habitat with a degrading delta translates to decreased water quality, reductions in ecosystem productivity and commercial fisheries yield, diminished biodiversity, and increased susceptibility to coastal flooding.

Worldwide, delta ecosystems are affected by degradation of river water quality, typically resulting from upstream land use patterns and waste treatment regimes for municipal and industrial sources in the catchment.

In the case of the Mississippi River, point-source pollution has declined substantially since passage of the Federal Water Pollution Control Act in 1948, and major subsequent amendments in the 1970s. Today, a primary water quality concern is large volumes of nutrient yields across the basin (especially the "Corn Belt" region), which has led to large increases in the nitrogen (nitrate) flux from the Mississippi River into the northern Gulf of Mexico. These increases from "nonpoint: sources, coincident with reductions in the silica (Si) flux (because of damming and impoundment), have led to changes in the quality (type) and quantity (amount) of productivity in the delta (Turner and Rabalais, 1991; Turner et al., 1998). Enhanced nutrient loads cannot be absorbed entirely by the delta ecosystem, so high levels of nitrate are reaching the coastal waters. Under relatively common stratification conditions caused by physical processes, the increased nitrate can result in algae bloom/crash cycles, leading to large areas (>1000's of km^2) of seasonal low-oxygen (hypoxic) waters along coastal Louisiana (Rabalais and Turner, 2006).

Many large river deltas have experienced profound biogeochemical shifts in the past several decades in response to global change and human intervention. Clear examples include the Danube and Mississippi River deltas, where shifts in nutrient dynamics (N vs. P vs. Si) limitation, biological productivity, and ecosystem metabolism are regulated by river flow and water quality (Humborg et al., 1997; Turner et al., 1998). Studies have shown that reduction of silica delivery to the coastal zone (because of upstream dams) reduces silicate to nitrate ratios, which leads to reductions in diatom productivity in coastal waters (Humborg et al., 1997; Turner et al., 1998).

The disciplines and types of research required to address river delta environmental dynamics include hydrodynamics, hydrology, sedimentology, geomorphology, landscape ecology, biogeochemistry, microbiology, ecosystem ecology, and modeling. Multidisciplinary studies that include and integrate these fields aim to identify and understand feedbacks and interactions between ecosystem components and hold the promise for advancing holistic system-level knowledge of river delta ecosystems.

DELTA CHALLENGES: AGENTS OF CHANGE

Historically, and particularly in the past several decades, deltaic regions such as the Mississippi have faced the expanding array of the changes and challenges introduced above. This section concentrates on a set of environmental processes that may be regarded as agents of change. They include physical and societal drivers of land and water use in coastal areas. Physical agents range from hydroclimatology to sediment transport, coastal subsidence, erosion, and large storms. Social forces include population change, economic development, infrastructure investment, technological change, and management institutions in the delta. Physical and social processes have coevolved to produce current delta conditions and challenges. Physical agents of change can generate problems for societies, which are amplified or dampened by infrastructural development and resource use, which in turn give rise to management and institutional responses to promote or regulate them. However, these agents of change often are coupled with one another, such as in the joint impacts of flood hazards, accelerated subsidence, and sea level rise.

The following agents of change serve here as examples of interactive factors that account for change in the Gulf Coast environment, and in selected delta environments internationally. Some are geophysical (e.g., hydrology, sediment); others involve human transformation (e.g., flood control, land development); and some involve socioeconomic processes (e.g., water management institutions). As deltas are delineated in a variety of ways (e.g., by river morphology in some and elevation in others), the analogues discussed in this section are qualitative in nature. These agents of change are closely interconnected, which leads to a broader systems approach for integrated water and environmental management discussed at the end of the chapter.

Hydroclimatic Variability

The Mississippi River basin (Figure 2-1) encompasses about 2 percent of the earth's land surface area, and about 41 percent of the area of the contiguous United States (Milliman and Meade, 1983; Meade, 1995). Only the Congo and Amazon river drainage basins generally are considered larger (Vanden Bossche and Bernacsek, 1990.

The Mississippi discharge has its source in precipitation, snowmelt, and groundwater spring flows, with losses to evapotranspiration and groundwater recharge. The eastern slope of the Rocky Mountains and the western slope of the Appalachian Mountains do not have significant glaciation or multiyear snowpacks, so the principal hydrological storage is in groundwater and lakes. The water budget for the Mississippi River above Vicksburg has three major elements: precipitation (835 mm/yr[1]), evapotranspiration (649 mm/yr), and discharge through the Mississippi (187 mm/yr; figures from Milly and Dunne, 2001). Only about 22 percent of the precipitation is actually discharged to the Gulf of Mexico.

Although the Mississippi River delta is unique in many of these attributes, it bears comparison with others on one or more variables (see Figure 2-2). For example, the Parana River may be an analogue for river discharge,

[1] All values are annual averages. Note that these numbers appear to be based on a drainage area of 2.8×10^6 km^2.

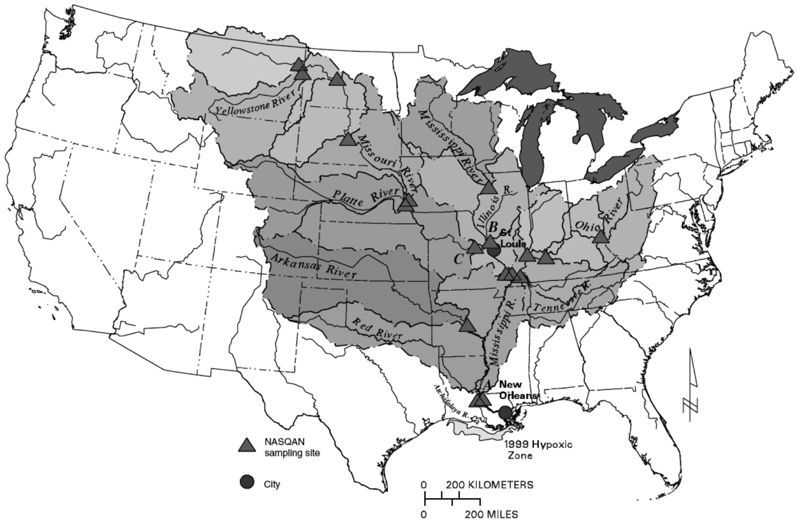

FIGURE 2-1 Mississippi River drainage basin.
SOURCE: Goolsby and Battaglin, 2001.

while the Indus and Volga rivers have deltas comparably the same size as the lower Mississippi.

Similarly, the climatic water budget in coastal Louisiana is characterized by 5 months that have a rough equilibrium between precipitation and evapotranspiration, with 7 months of surplus precipitation and runoff. This is analogous with a small number of other large, subtropical river basins, located primarily in East Asia, although as will be discussed further, construction of analogies can be based upon partial similarities and differences between deltas.

Sediment Mass Balance

The morphology of the Mississippi River delta reflects a balance between supply of sediment from the upstream catchment and erosion and redistribution of sediments by coastal processes. Over the twentieth century, the sediment supply to the Mississippi River delta has decreased from about 400 million metric tons per year to about 145 million metric tons per year because of upstream dams, erosion control, and channel engineering works (Meade and Moody, 2010). A large portion of the reduced sediment volume delivery to coastal Louisiana can be attributed to structures built on the Missouri River, which was a broad, shallow, geomorphologically-active

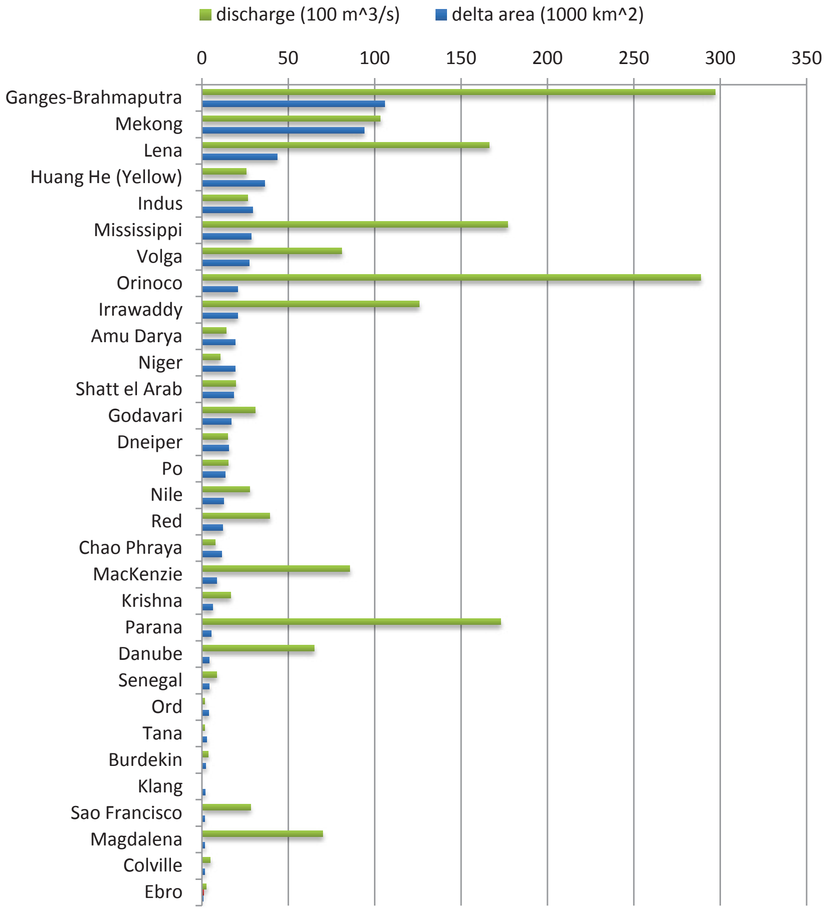

FIGURE 2-2 Some major river deltas ranked by delta area.
SOURCE: World Delta Database, contributions by Coleman and Huh, 2004.

channel before construction of six large mainstem multipurpose reservoirs in the 1930s to 1960s, along with hundreds of miles of river training structures below the downstream mainstem dam at Gavins Point. The dams and river control and bank stabilization structures were built by the U.S. Army Corps of Engineers (NRC, 2011a). Alteration of sediment mass balance along the Missouri River is a major factor leading to the coastal retreat documented in recent decades.

Within the lower Mississippi basin, an important human-induced alteration is the prevention of distributary channel avulsion, channel breakouts, and spreading of sediment-charged floodwaters across the deltaic plain. To maintain existing navigation, the flow of the Mississippi is constricted within the current "birds-foot" channel outlet to the Gulf. This constraint has the effect of preventing the reduced sediment load still carried by the river from depositing on the deltaic plain between distributary channels. A large portion of the river's sediment load is directed into the deep waters of the Gulf, where it cannot contribute to maintaining the coastal delta.

Syvitski et al. (2009) estimate a 48 percent reduction in sediment delivery for the Mississippi River delta over the twentieth century, which is comparable with loss of sediment supply to deltas in Europe and South Asia (Table 2-1). For the Mississippi, the loss corresponds to a reduction of delta aggradation from 2 mm/yr in the twentieth century to 0.3 mm/yr in the early twenty-first century. Interestingly, Table 2-1 indicates that the percent reduction in distributary channels of the Mississippi delta is "unknown."

Subsidence

Subsidence refers to a lowering of the elevation of the ground surface, usually relative to historical mean sea level or similar datum. Subsidence can occur from natural or anthropogenic mechanisms, or as commonly is the case in deltas, from a combination of the two. Natural mechanisms in coastal areas include isostatic adjustments, sediment compaction, adjustments of deltaic landforms in response to crustal loading and compaction of accumulated sediments, and tectonics. Anthropogenic causes of subsidence are typically from resource extraction (e.g., groundwater or oil and gas), which allows deep strata to compact; reduced sediment loads from the river basin upstream (often due to trapping of sediment behind dams), which reduces the rate at which fresh sediment deposition can compensate for subsidence; and wetland drainage, which exposes organic material in soil to the atmosphere, leading to increased rates of oxidative weathering and soil decomposition.

The relative significance of these processes is part of an ongoing debate regarding river deltas around the world (Vermaat and Eleveld, 2013). A qualitative comparison of 10 deltas by the Delta Alliance, an international knowledge network based in Wageningen in the Netherlands, indicates that only the California Bay Delta and Chiliwung have a severity of subsidence comparable to that of the Mississippi (Table 2-2).

A map of projected subsidence ranges for southern Louisiana (Figure 2-3) shows the greatest subsidence rates in the southern part of the delta. Many of the factors described above are at work in the Mississippi Delta (Reed and Yuill, 2009), and many prior studies have emphasized the role of oil and gas extraction and reduced sediment delivery from the river basin upstream (e.g., NRC, 2006). However, outside of geological circles, it ap-

TABLE 2-1 Delta Database with Key Environmental Data

Delta	Area < 2 m above sea level (km^2)	Storm-surge area (km^2)*	Recent area of river flooding (km^2)	Recent area of *in situ* flooding (km^2)	Sediment reduction (%)	Floodplain or delta flow diversion	Distributary channel reduction (%)	Subsurface water, oil and gas mining	Early-twentieth-century aggradation rate ($mm\ yr^{-1}$)	Twenty-first-century aggradation rate ($mm\ yr^{-1}$)	Relative sea-level rise ($mm\ yr^{-1}$)
Deltas not at risk: aggradation rates unchanged, minimal anthropogenic subsidence											
Amazon, Brazil	1,960[†]	0; LP	0	9,340	0	No	0	0	0.4	0.4	Unknown
Congo[‡], DRC	460	0; LP	0	0	20	No	0	0	0.2	0.2	Unknown
Fly, Papua New Guinea	70[†]	0; MP	140	280	0	No	0	0	5	5	0.5
Orinoco, Venezuela	1,800[†]	0; MP	3,560	3,600	0	No	0	Unknown	1.3	1.3	0.8–3
Mahaka, Borneo	300	0; LP	0	370	0	No	Unknown	0	0.2	0.2	Unknown
Deltas at risk: reduction in aggradation, but rates still exceed relative sea-level rise											
Amur, Russia	1,250	0; LP	0	0	0	No	0	0	2	1.1	1
Danube, Romania	3,670	1,050	2,100	840	63	Yes	0	Minor	3	1	1.2
Han, Korea	70	60	60	0	27	No	0	0	3	2	0.6
Limpopo, Mozambique	150	120	200	0	30	No	0	0	7	5	0.3
Deltas at greater risk: reduction in aggradation where rates no longer exceed relative sea-level rise											
Brahmani, India	640	1,100	3,380	1,580	50	Yes	0	Major	2	1	1.3
Godavari, India	170	660	220	1,100	40	Yes	0	Major	7	2	~3
Indus, Pakistan	4,750	3,390	680	1,700	80	Yes	80	Minor	8	1	>1.1
Mahanadi, India	150	1,480	2,060	1,770	74	Yes	40	Moderate	2	0.3	1.3
Parana, Argentina	3,600	0; LP	5,190	2,600	60	No	Unknown	Unknown	2	0.5	2-3
Vistula, Poland	1,490	0; LP	200	0	20	Yes	75	Unknown	1.1	0	1.8

Deltas in peril: reduction in aggradation plus accelerated compaction overwhelming rates of global sea-level rise											
Ganges‡, Bangladesh	6,170†	10,500	52,800	42,300	30	Yes	37	Major	3	2	8–18
Irrawaddy, Myanmar	1,100	15,000	7,600	6,100	30	No	20	Moderate	2	1.4	3.4–6
Magdalena, Colombia	790	1,120	750	750	0	Yes	70	Moderate	6	3	5.3–6.6
Mekong, Vietnam	20,900	9,800	36,750	17,100	12	No	0	Moderate	0.5	0.4	6
Mississippi, USA	7,140†	13,500	0	11,600	48	Yes	Unknown	Major	2	0.3	5–25
Niger, Nigeria	350†	1,700	2,570	3,400	50	No	30	Major	0.6	0.3	7–32
Tigris‡, Iraq	9,700	1,730	770	960	50	Yes	38	Major	4	2	4–5
Deltas in greater peril: virtually no aggradation and/or very high accelerated compaction											
Chao Phraya, Thailand	1,780	800	4,000	1,600	85	Yes	30	Major	0.2	0	13–150
Colorado, Mexico	700	0; MP	0	0	100	Yes	0	Major	34	0	2–5
Krishna, India	250	840	1,160	740	94	Yes	0	Major	7	0.4	~3
Nile, Egypt	9,440	0; LP	0	0	98	Yes	75	Major	1.3	0	4.8
Pearl‡, China	3,720	1,040	2,600	520	67	Yes	0	Moderate	3	0.5	7.5
Po, Italy	630	0; LP	0	320	50	No	40	Major	3	0	4–60
Rhone, France	1,140	0; LP	920	0	30	No	40	Minor	7	1	2–6
Sao Francisco, Brazil	80	0; LP	0	0	70	Yes	0	Minor	2	0.2	3–10
Tone‡, Japan	410	220	0	160	30	Yes	§	Major	4	0	>10
Yangtze‡, China	7,080	6,700	3,330	6,670	70	Yes	0	Major	1.1	0	3–28
Yellow‡, China	3,420	1,430	0	0	90	Yes	80	Major	49	0	8–23

* LP, little potential; MP, moderate potential; SP, significant potential.
† Significant canopy cover renders these SRTM elevation estimates conservative.
‡ Alternative names: Congo and Zaire; Ganges and Ganges-Brahmaputra; Pearl and Zhujiang; Tigris and Tigris-Euphrates and Shatt al Arab; Tone and Edo; Yangtze and Changjiang; Yellow and Huanghe.

NOTE: Storm surge, river (distributary) channel, and precipitation (*in situ*) flooding are from MODIS satellite data since 2000. The level of sediment-load reduction is across the twentieth century, as is the reduction in distributary and subsurface mining. Rates of relative sea-level rise are time-variable and the ranges provided cover either different times or different areas of a delta.
SOURCE: Syvitski et al., 2009.

TABLE 2-2 Comparison of Subsidence in the Delta Alliance Comparative Study

	Demographic trends	Economic developments	Technological developments	Climate change	Subsidence
Nile	•••	••	••	•••	••
Incomati	•	••••	••	•••	•
Ganges-Brahmaputra-Meghna delta	••	•••	••	••••	••
Yangtze	•••	••••	••	••	••
Ciliwung	••••	•••	••	•••	••••
Mekong	••	••••	••	•••	••
Rhine-Meuse	•	••	•••	••	••
Danube	•	•	•	••	•
California Bay-Delta	••	••	••	•••	••••
Mississippi River Delta	•	••	•••	•••	•••

• *minimal impacts, now and in the near future (around 10 years)*
•• *small impacts*
••• *medium impacts*
•••• *severe impacts*

SOURCE: Bucks et al., 2010.

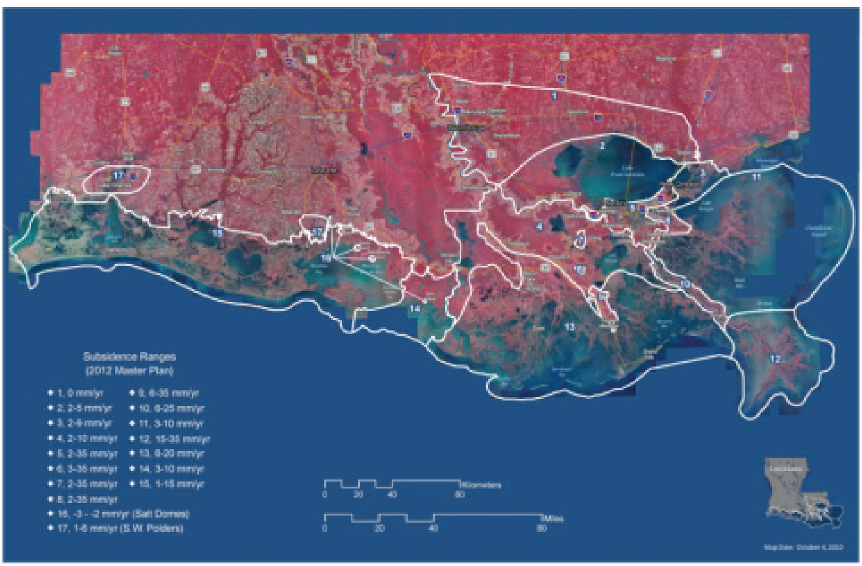

FIGURE 2-3 Map of projected subsidence ranges for south Louisiana generated by the Subsidence Advisory Panel for the Louisiana CPRA Master Plan 2012 Update, following a meeting on October 14, 2010.
SOURCE: CPRA, 2010.

pears there has been less recognition of the underlying geological processes of delta deposition and adjustment, in which important growth faults exert a strong influence on subsidence rates.

Nutrient Balances

Nutrients are essential building blocks that support biological production in the environment. The availability of the major macronutrients, nitrogen and phosphorus, often limits biological production in aquatic systems. In shallow coastal regions, however, these nutrients may be present at high levels due to nutrient inputs from agricultural runoff, sewage or septic inputs, industrial activity, and general development. High nutrient levels drive eutrophication and degrade water quality and may threaten coastal environments, especially large deltas like the Mississippi (Rabalais and Turner, 2006).

In general, nutrients are not the only chemical constituent used to define water quality; rather, it is commonly defined by the concentration of chemical (e.g. dissolved oxygen, plant nutrients, toxins, etc.) and biological (e.g., coliform bacteria) components. In the Mississippi River delta, the concentration and flux of inorganic nitrogen are often key drivers of coastal water quality as high nitrogen fluxes lead to increased plant productivity and biomass, stimulation of noxious algal species, increased rates of organic matter deposition, and, ultimately, hypoxia. Hypoxia leads to habitat degradation and may have negative consequences for Gulf coastal fisheries (Figure 2-4). This cascade of consequences has occurred in the Mississippi River delta region, as well as in other coastal ecosystems across the globe (Figure 2-5; also see Zhao et al., 2012).

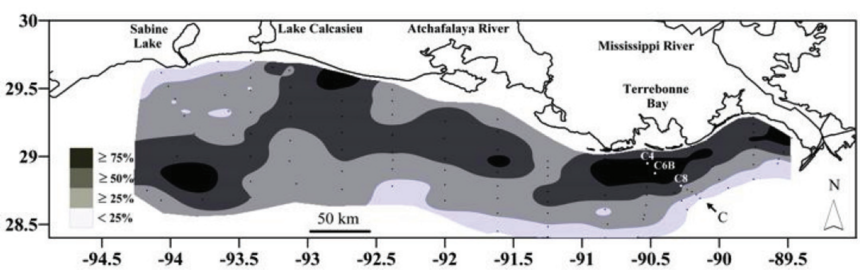

FIGURE 2-4 Frequency of midsummer hypoxia along coastal Louisiana.
SOURCE: Modified from Rabalais et al., 2007.

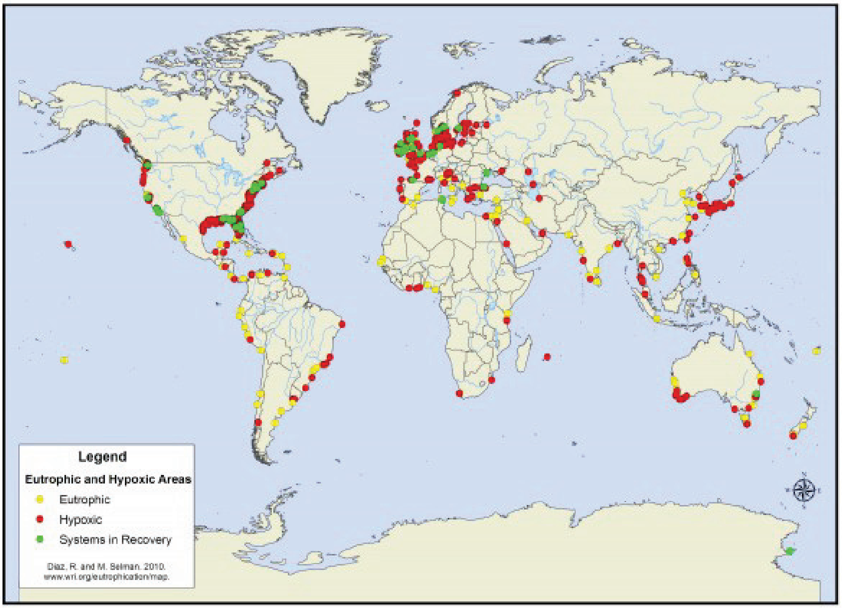

FIGURE 2-5 World hypoxic and eutrophic coastal areas.
SOURCE: WRI, 2010.

Salinity Dynamics

Coastal and delta ecosystems are the meeting place for fresh- and saltwater. The brackish mixing zones in deltas and estuaries are critical within the life cycles of many oceanic species, often providing spawning grounds or juvenile refuge. The distribution and activity of plants, animals, and microorganisms respond to changes in salinity; thus, factors altering salinity distributions are major regulators of coastal ecosystem dynamics. Increased salinity alters plant distributions and can stimulate microbial metabolism in marsh soils, leading to increased respiration rates (Weston et al., 2006). Sea level rise coupled with land subsidence represents a stressor of coastal ecosystems through changes in salinity dynamics that cascade from physical alterations in the range and distribution of water depths. The variability of salinity at any location is affected by the freshwater available, the marsh plants that constrain flow conditions and remove freshwater through evapotranspiration, and water depth. Increasing salinities can have a direct effect on viability of species with limited salinity ranges (e.g., oysters), and indirectly by increasing frequency of hypoxia. In the absence of wind or strong water currents, lighter freshwater flows over the top of denser saltwater creating stratification that can impede oxygen replenishment and lead to hypoxia at the benthos. Such layers might be thin and episodic (Hodges et al., 2011), but nevertheless impact the benthic ecosystem (Montagna and Ritter, 2006). Wind and strong water currents serve to break down stratification and replenish benthic oxygen levels, but deeper water requires more energy to ensure complete mixing. Thus, changes in water depths in the Mississippi River delta and along the Louisiana coast are likely to alter existing relationships between salinity gradients, mixing, and oxygen replenishment. Water withdrawals, as well as reduced flood peaks (e.g., due to upstream dams and flood control operations), also would further reduce mixing and lead to increased salinities in the coastal zone.

Salts in windborne spray from breaking waves also are transported inland by winds, affecting soil salinity. The response of coupled biogeochemical processes in coastal systems to changes in salinity is not fully understood but, clearly, maintaining stable salinity patterns is critical for sustenance of productive coastal ecosystems. Salinity dynamics and associated resource management challenges in the Louisiana delta may be compared and contrasted with those of other deltas, such as the Bengal and Mekong regions (USGS, 2013). Saltwater intrusion is even more severe in arid irrigated basins and deltas of the Colorado, Indus, and Nile rivers.

Flood Mitigation and Hurricane Protection

Southern Louisiana is subjected to the hydrologic hazards of both lower Mississippi River flooding and Gulf of Mexico hurricanes. Water-related natural hazards have had profound effects in shaping landforms, and development patterns, across southern Louisiana. From the great Mississippi River flood of 1927 and its lasting impacts on the region and nation (see Barry, 1997), to the devastation of Hurricane Katrina in 2005, the region has been the site of some of the nation's most damaging and disruptive floods and hurricanes.

Following the 1927 Mississippi River flood, the U.S. Congress passed the 1928 Flood Control Act that authorized the Mississippi River and Tributaries (MR & T) project. Responsibility for developing and implementing the project was assigned to the Mississippi River Commission. The MR & T has four major elements: (1) levees for containing flood flows; (2) floodways to pass excess flows past critical reaches of the Mississippi River, and around communities and valuable infrastructure; (3) channel improvement and stabilization activities to ensure a reliable navigation channel, increase the river's flood-carrying capacity, and protect the levee system; and (4) tributary basin improvements, such as dams, reservoirs, and pumping plants and stations (USACE, 2013a). The MR & T is the largest flood control project in the world. It includes huge mainstem levees along the lower Mississippi River that provide levels of flood protection for Baton Rouge, New Orleans, and other communities along the river.

The MR & T project has had extensive and profound effects on lower Mississippi River, and Atchafalaya River, hydrology. The project, via the Old River Control Structure located near Simmesport, Louisiana, diverts 30 percent of Mississippi River discharge into the Atchafalaya River and valley. The project's flood control levees inhibit distribution of sediments in high water into extensive floodplain areas. It also must be noted that the MR & T system has performed well during periods of high river flows; in 2011, for example, during extremely high Mississippi River flows, the system performed much as had been envisioned decades ago.

Regarding threats from hurricanes and related storm surge, the primary means for structural protection is the Greater New Orleans Hurricane and Storm Damage Risk Reduction System. There is a long, complex, and interesting history of multiple federal authorizations for the construction of various segments of this system across the New Orleans region (see Woolley and Shabman, 2008). Significant federal planning—including Corps of Engineers' design proposals and congressional authorizations—for hurricane protection for New Orleans and the surrounding metropolitan areas date back to the 1950s, when the Corps began studies for the Lake Pontchartrain and Vicinity Hurricane Protection Project. This history of hurricane project development includes changes in preferences for Corps plans; lawsuits and injunctions; complex relations and relative responsibilities between the Corps, the state of Louisiana, and levee districts and other parish-level entities; and hurricanes that changed perceptions of the system and protection (notably Hurricane Betsy in 1965).

Hurricane Katrina in late August 2005 exposed the flaws and inadequacies in the historical development of New Orleans hurricane protection. In Katrina's aftermath, the U.S. Department of the Army established the Interagency Performance Evaluation Task Force (IPET) to assess the system's performance during Katrina. The IPET evaluation produced numerous reports in its existence from 2005 to 2008. Among its many conclusions, it stated that the hurricane protection system ". . . did not perform as a system," that the system was constructed "in many separate steps over a long period of time" and represented a history of "continuous incompleteness" (IPET, 2008).

Following Katrina, over 10 billion federal dollars were invested in New Orleans' hurricane and flood protection system, including repairs and strengthening on hundreds of miles of levees, walls, and gates. Since Hurricane Katrina (and Rita) in 2005, there has been renewed national-level interest in southern Louisiana and Gulf hurricane and storm surge protection, and in ways in which levees, sea walls, population resettlement, evacuation, floodproofing, and landscape restoration might be better

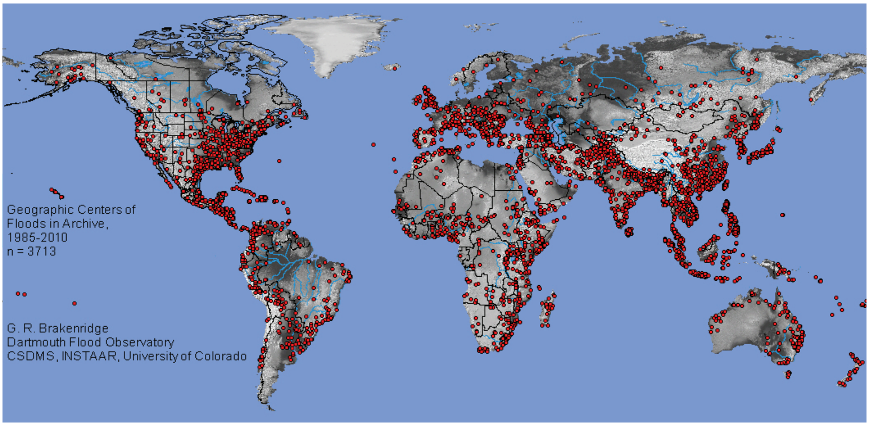

FIGURE 2-6 Geographic centers of flood events, 1985-2010.
SOURCE: Dartmouth Flood Observatory, 2010.

integrated to reduce the region's exposure and vulnerability (NRC, 2009; RAND, 2011). From a global perspective, the distribution of flood losses and flood control efforts is shaped by population density and land development in major floodplains and coastal areas. These hazards generally have their most destructive effects in the major deltas of Asia (Figure 2-6). Centers with information that compare international flood events, losses, and trends include the maps and records of the University of Colorado's Dartmouth Flood Observatory[2] (Figure 2-6; NASA's near real-time flood mapping imagery,[3] and the Center for Research on the Epidemiology of Disasters EMDAT database.[4]

Deltas that experience large numbers of tropical cyclones provide comparisons with the Mississippi River delta (e.g., as mapped by the Joint Typhoon Warning Center; NASA; NOAA; and others). Global historical tropical storm tracks (Figure 2-7) indicate that partial analogues to the Mississippi delta can be found in East, Southeast, and South Asia. The analogues are partial because storm risk also depends upon bathymetry, tidal range, and coastal population and infrastructure at risk (e.g., Brakenridge et al., 2013). Tropical storms prompt questions about the current degree of vulnerability for human populations, infrastructure, settlement patterns, and commerce.

---

[2] See http://floodobservatory.colorado.edu.

[3] See http://oas.gsfc.nasa.gov/floodmap/index.html.

[4] See http://www.emdat.be.

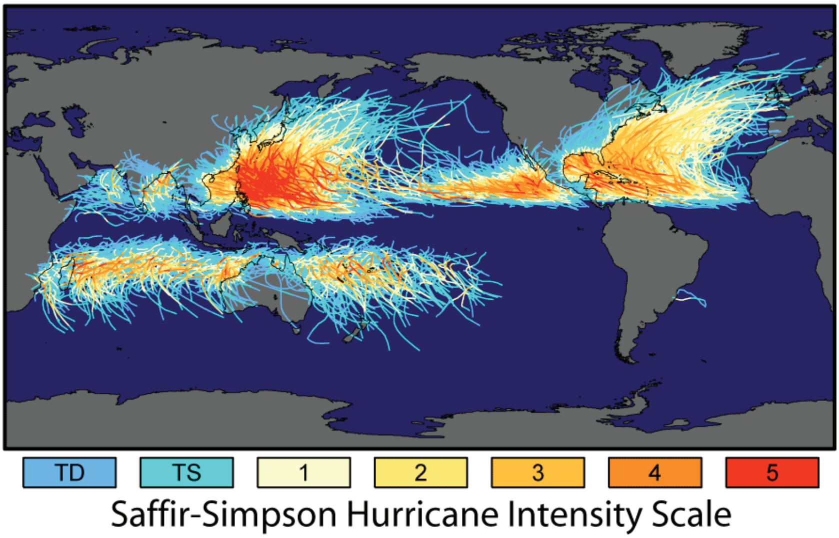

FIGURE 2-7 Tracks and intensity of all tropical storms.
NOTE: TD: tropical depression. TS: tropical storm.
SOURCE: NASA, 2013.

Climate Change and Sea Level Rise

Climate change and accelerated sea level rise are chronic phenomena that exacerbate natural forcing functions. Hydrologic alterations, such as droughts, floods, and large storms (hurricanes, nor'easters), can lead to rapid change in coastal zones, including exacerbation of coastal erosion (Pijnappels et al., 2010). Regional or global shifts in climate may occur over the indefinite future and affect environmental and social processes in the Gulf delta and coastal regions. Linkages between regional environmental change and global climate change are distinctive in that they are likely to be manifested only gradually, as compared with other types of change mentioned above, and because their effects are masked over short intervals by local or regional climate variability. The topics of nonstationarity and its implications for climate and hydrologic systems, and water management and decision making, have widespread implications and attract extensive scientific and public policy interest (see Colorado Water Institute, 2010).

Regarding the implications of sea level rise, changes in climate may affect sea level rise globally; but there may be regional differences in sea level rise, as well, because of differences in geologic factors such as subsidence and tectonics, which raise or lower coastal land masses and landforms.

Large-scale climate variations, such as El Niño and the Pacific Decadal Oscillation, also raise or lower regional sea level height (NRC, 2012). Increasing sea level heights would have definable consequences for the coastal zone, including vulnerability of human populations to storms or floods. Figure 2-8 illustrates sea level rise predictions along U.S. coastal areas, with the highest predicted rates for the Louisiana and Texas gulf coasts, while Figure 2-9 illustrates global sea level rise estimates.

Significant regional changes in other aspects of climate could occur, but are difficult to anticipate and especially difficult to translate into specific effects and adaptation plans in the Gulf Coast environment (cf. Van der Most, 2009). An assessment from the Intergovernmental Panel on Climate Change of global coastal vulnerability to sea level rise put the Mississippi delta in the “high” but not “extreme” category of population displacement related to an estimated eustatic (worldwide, uniform change) sea level rise of 5-7 mm/yr and the Mississippi delta’s relatively low population density indicate 5-25 mm/yr (Figure 2-10; Ericson, Vörösmarty et al., 2006; Nicholls et al., 2007; Syvitski et al., 2009). Other deltas in the same category are the Godavari delta in India, Changjiang delta in China, Niger in Nigeria, and Shatt al Arab in Iraq. Analogues in the more “extreme” category are the Ganges-Brahmaputra and Mekong.

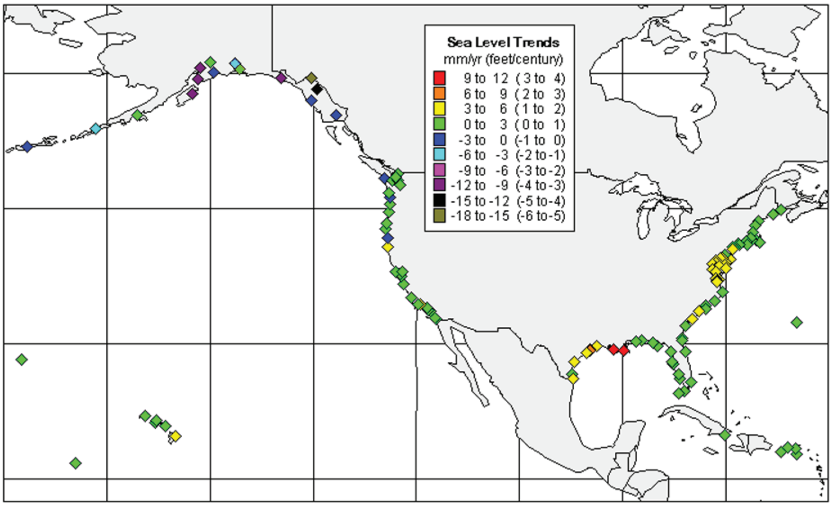

FIGURE 2-8 Regional mean sea level trends.
SOURCE: NOAA, 2013.

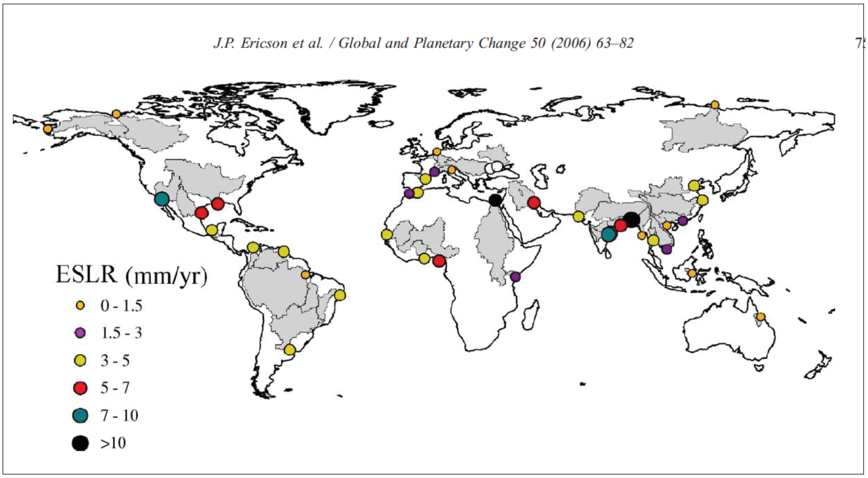

FIGURE 2-9 Global distribution of estimated seal level rise (ESLR) under baseline conditions for 40 deltas.
SOURCE: Ericson, Vörösmarty et al., 2006.

FIGURE 2-10 Relative vulnerability of coastal deltas as shown by the population potentially displaced by current sea-level trends to 2050 (Extreme = >1 million people displaced; High = 1 million to 50,000; Medium = 50,000 to 5,000).
SOURCE: Nicholls et al., 2007.

Commercial Navigation and Dredging

Commercial navigation on the lower Mississippi River is one of the region's important and vital economic sectors, which also has great national economic significance. Some 6,000 vessels and 300 million tons of cargo travel up and down the Mississippi River each year, including over half of the nation's grain exports. In 2010, more than 10,000 vessels transited South Pass, one of the three branches of the mouth of the Mississippi River (Lorino, 2011).

The Ports of New Orleans, South Louisana, Plaquemines, and Baton Rouge are four of the top 13 U.S. ports based on volume of cargo handled (U.S. DOT, 2013). The Ports of New Orleans and south Louisiana together form one of the world's largest port systems in terms of bulk tonnage. The Port of New Orleans is served by six major railroads, more than any port in the United States. Port of New Orleans facilities include over 204 hectares of cargo-handling areas and more than 12 hectares of covered storage, and its Henry Clay Avenue and Milan Street terminals are served by the world's longest wharf (Port of New Orleans, 2013).

Historically, the U.S. Army Corps of Engineers has dredged the river to depths that allow vessels with greater than 45-foot drafts to navigate the river's passes into and out of the river. Sufficient draft depth to support commercial navigation clearly is an issue of great importance to commercial navigation, and any proposals that the Corps of Engineers might reduce its dredging activities along the lower river are of great concern to the shipping industry (see Ryan, T.P., 2012). Commercial navigation interests also have concerns about the potential effects of proposed diversions along the lower Mississippi River to enhance wetlands creation (as proposed in the Louisiana 2012 Coastal Master Plan). Dredging in the lower Mississippi River creates preferential deep-water paths for freshwater to rapidly enter the Gulf of Mexico, whereas diversions attempt to spread freshwater over broader areas. Diversions thus could negatively affect the commercial navigation sector, if diverted flows either affect river water levels (reducing available ship draft) or induce shoaling within the river downstream of the diversion. Interactions between diversions, and resulting changes in sediment delivery and deposition, are of critical importance given the economic prominence and value of the shipping industry, barge operators, pilots associations, and the energy industry.

A harbinger of possible tensions between navigation and diversions is the West Bay Diversion, which is a human-made opening on the west side of the Mississippi River south of Venice, Louisiana, and 4.7 miles above Head of Passes. This diversion was designed to create 9,832 acres of wetlands over a 20-year project life, by allowing 20,000 cubic feet per second of river water to flow into West Bay (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 2013). The wetland creation project was funded by the U.S. federal Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) of 1990.

After wetland project construction in 2003, the anchorage at Pilottown, Louisiana required dredging, leading some to conclude that the diversion caused river shoaling. Concerns about ongoing dredging costs almost led to closure of the diversion, which would have been a strong indication that navigational interests trump restoration. However, the Corps of Engineers showed that only 25 percent of the dredging is a result of the diversion; therefore, dredging costs attributable to the diversion were lower than expected, and the diversion continues to create land.

Land Development—Rural, Industrial, Residential, and Urban

Although not as densely populated as some large river deltas around the world, the Mississippi River Delta is home to an impressive concentration of industrial and navigational infrastructure, the maintenance of which largely motivates efforts to preserve the status quo of the current birds' foot delta mouth and petroleum industry logistics centers, such as Port Fouchon. With the pressure of increased population, large areas—especially contiguous with New Orleans—have been developed for housing and commercial uses, mostly low-lying "back swamp" areas that were considered uninhabitable before the advent of powerful pumps capable of draining the land (Campanella, 2002). Once areas are settled, the presence of the populations there creates pressure to build levees, and over time, more and larger levees, which in turn can encourage more development, and the larger populations at risk can then increase the demand for structural protection (White, 1945; Werner and McNamara, 2007).

Settlement patterns and commercial use of coastal lands, including marshes, create social interests that lead to support for or opposition to environmental management. Examples include support for specific flood control or sediment augmentation plans motivated by a desire to preserve property, and opposition to the same kinds of plans on grounds of expected reduction of land values or impairment in harvest of fish or shellfish. The long-term record of settlement and urbanization has fascinating trajectories, particularly in the New Orleans metropolitan area, which has experienced population loss, postdisaster redevelopment, and wider changes in urbanism in recent years (Colten et al., 2008; Campanella, 2010). Comparative social sciences research is also useful for assessing the vulnerability of different social groups (Slack et al., 2009).

Energy and Petrochemical Development and Operations

Oil and gas development in the Gulf region began over a century ago. It expanded rapidly in the Mississippi River delta during the third quarter of the twentieth century, after which oil production moved increasingly offshore, while significant gas production in the delta continues (Figures 2-11 and 2-12). Legacy channels, pipeline aging, and associated hazards

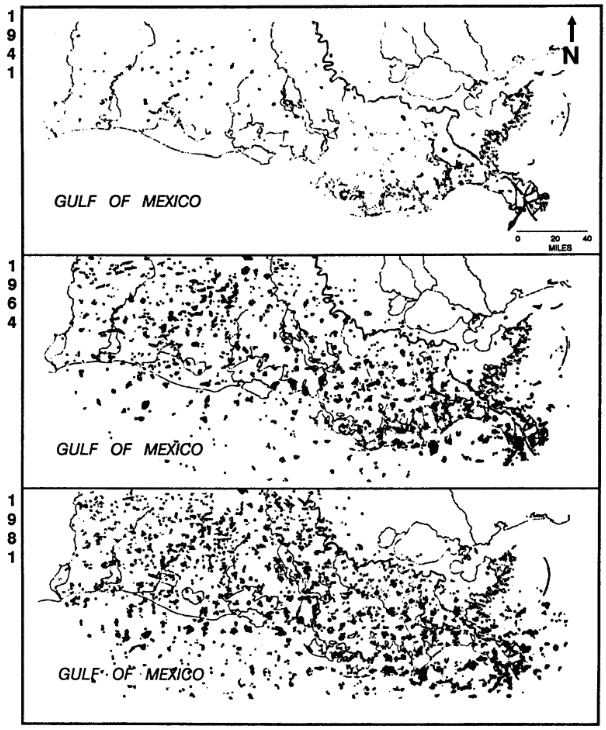

FIGURE 2-11 Oil and gas fields in southern Louisiana in 1941, 1964, and 1981.
SOURCE: Turner, 1987.

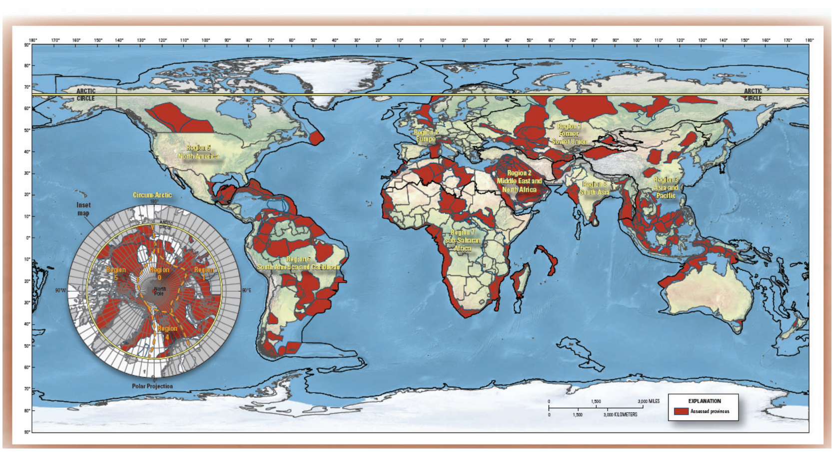

FIGURE 2-12 Estimates of undiscovered conventional oil and gas resources of the world, fact sheet 2012-3028.
SOURCE: Schenk, 2012.

remain. The infrastructure and operations of the energy industry in the Gulf region affect environmental resources through channelization and diking, which affect routing of water and sediment within wetlands. Pipeline and extraction channels disrupt water flow and accelerate erosion, while pumping increases rates of local subsidence. Changes in standard practice and remediation measures following the construction phase of energy extraction have the potential to restore natural features of marsh affected by routine operations that follow construction.

Many deltas in other regions of the world have oil and gas production. One of the largest and arguably most problematic cases is the Niger delta where environmental contamination and conflict have escalated. The Orinoco and Nile deltas have deltaic oil production, as do offshore areas in the north Indian Ocean and Arctic Sea. As in the Mississippi, production in some of these regions is moving from coastal to offshore fields.

Fisheries and Biodiversity

Fish and shellfish habitat and abundance depend upon all of the agents of change discussed above. Yields from the Gulf delta region are monitored and regulated in an attempt to ensure sustained yield. Environmental impairment caused by the Deepwater Horizon oil spill, multiple severe storms, and gradual loss of habitat can be expected to reduce optimum yield of commercially important species. To plan for habitat conservation and restoration projects, the Louisiana 2012 Coastal Master Plan commissioned 14 habitat suitability index reports for species of commercial, sport, and ecological interest that included American alligator, crawfish, eastern oyster, brown and white shrimp, largemouth bass and spotted sea trout, otter, muskrat, and several species of waterfowl (CPRA, 2012, apps. D5-D18).

Worldwide, deltas are valued for their biological diversity and estuarine ecological services (Day et al., 2012). The Danube delta stands out as a region that has been formally protected as a biosphere reserve and United Nations Economic, Scientific, and Cultural Organization (UNESCO) World Heritage Site of "outstanding universal value" since the early 1990s. It includes lands in Romania, Ukraine, and Moldova. It has been described as Europe's best-preserved delta (UNESCO, 2013), and it also has been noted for progress made in rules for navigation dredging and restoration, and architecture and building activities. The Sundarbans mangrove forest of Bangladesh and India is another major international deltaic region listed as a UNESCO World Heritage Site.[5] UNESCO has raised concerns about the infrastructure for ecological monitoring and protection, which may be

[5] For more information, see: http://whc.unesco.org/en/list/798/; and: http://whc.unesco.org/en/list/452.

an opportunity for collaborative international research. Finally, the U.S. Geological Survey DRAGON (2013) program has initiated a collaborative fisheries project in the Mekong basin that provides an analogue with the Mississippi River delta.

Water Management Institutions

It may seem unusual to regard water management institutions as agents of change, but they guide infrastructure development and natural resources use in ways that have human and environmental consquences in lower riparian and deltaic regions. Institutions, broadly defined, include water laws, policies, and organizations, along with the social practices through which they operate (Ingram et al., 1984). They are designed to have certain effects on water and related land resources; and to avoid, mitigate, or correct others (Ostrom, 1990). To be effective in any of these ways, water management institutions require legitimacy and are to be implemented by the societies that create and modify them. The effects of diverse water institutions may complement or conflict with one another. The absence of water institutions also has impacts (Galloway, 2011). Thus, the nature and roles of institutional diversity, dynamics, and change play important roles in complex environmental systems (Ostrom, 2005).

To be more specific about effects of water institutions in deltaic areas, it is important to understand how they respond to biogeophysical agents of change, such as floods and hurricanes, with greater or lesser degrees of effectiveness and sustainability. Timely institutional response to environmental change, extreme events, and slow-onset hazards (such as drought) in deltaic regions requires nonstructural institutions that enhance preparedness, warning, and evacuation, as well as structural measures of adjustment (Glantz, 1999; White, 1945). The history of the Mississippi River delta development and management also underscores the importance of effective relationships between specific water institutions and broader governance structures.

Governance includes social roles and responsibilities, including private and nongovernmental actors who affect the structure and processes of deltaic water, land, and environmental management. Governance shapes and is shaped by major social trends from privatization to participation, risk behavior, decentralization, and globalization. Although institutional and governance research have expanded recently in the fields of water and environmental management, they may be less mainstreamed in Mississippi River delta research than in the Rhine-Meuse delta and other regions (Table 2-3). Over the course of centuries, Dutch water boards (*watershappen*) have consolidated from several thousand down to the current 25 (Unie

TABLE 2-3 Comparative Overview of Scorecards of the 10 Deltas Studied, Including Governance Scores

	Land and water use (occupation layer)	Infra-structure (network layer)	Natural Resources (base layer)	Governance	Resilience & Sustainability Indicator		
					Current	Moderate Scenario	Extreme scenario
Nile delta	--	0	-	0	-	-	--
Incomati delta	0	-	-	-	-	-	--
Ganges-Brahmaputra-Meghna delta	--	--	--	0	--	-	--
Yangtze delta	-	+	-	0	0	0	--
Ciliwung delta	--	--	--	-	--	--	-
Mekong delta	0	0	-	0	0	+	0
Rhine-Meuse delta	+	++	0	+	+	0	-
Danube delta	+	+	+	0	+	0	0
California Bay-Delta	0	-	-	0	-	0	-
Mississippi River Delta	0	0	-	0	-	0	-

resilience/sustainability: ++*(very good)*, + *(good)*, 0 *(medium)*, – *(low)*, –– *(very low)*

SOURCE: Bucks et al., 2010.

van Waterschappen, 2013). The Delta Alliance 10-deltas study flagged "governance" as a research gap in the Mississippi delta (Bucks et al., 2010).

Cumulative Impacts of Agents of Change: The Example of Deltaic Land Loss

The agents of change discussed above interact with one another and can amplify or offset one another in various environmental processes in lower basin and coastal deltaic regions. A good example is the core concern with deltaic land loss in coastal Louisiana. Many deltaic regions, including the lower Mississippi, face increasing rates of coastal land loss. This land loss may be regarded as the cumulative and joint effect of almost all the agents of change listed above.

Detailed reconstructions of historical processes of land loss in coastal Louisiana indicate and project net losses at differential rates for all but a very few small areas of the coast (Blum and Roberts, 2009). These exceptions are important research areas for understanding land-building processes. International analysis by Ericson, Vörösmarty et al. (2006) estimates future land losses to sea level rise in the Mississippi delta between 2000 and 2050 at almost 20 percent. Two other international deltas with similar magnitudes of estimated losses are the Godavari in India (22.5 percent) and the Orinoco in Venezuela (21 percent) (Table 2-4).

A SYSTEMS APPROACH TO INTEGRATED WATER AND ENVIRONMENTAL MANAGEMENT

The foregoing overview of environmental agents of change in the Mississippi River delta region and selected international delta analogues indicate that agents of change have cumulative effects. One major challenge for environmental research in the Gulf is to separate and quantify the effects of specific agents of change as a means of providing scientific guidance for remediation and modification of standard practices of human activities in the Delta. However, there are myriad unmet research needs associated with each agent of change, and their coupled nature suggests the advisability of a systems approach to analysis of challenges in the Mississippi delta and other large deltaic regions.

A Human-Environmental Systems Research Approach

The greater challenge for research of practical value is to treat deltas as integrated water and environmental systems. Relevant to this approach was a historical breakthrough in water systems planning in the Harvard Water Program and related efforts in the mid-twentieth century exemplified by the *Design of Water Resource Systems* (Maass et al., 1962). That work drew together advances in multiobjective water infrastructure planning, economic simulation and optimization models, synthetic hydrology methods, and new computational tools. It was led by a professor of government at Harvard and included institutional and political analysis. It did not include ecosystem modeling or behavioral decision making, but concurrently ecologists such as Eugene and Howard Odum were developing ecological and energy models that were applied specifically to wetland and estuarine systems (Day et al., 2012; Odum, 1969; Odum, 1971). Geographer Gilbert F. White (1945) pioneered behavioral sciences approaches to flood hazards and floodplain settlement. Through these and many other contributions, the Mississippi River valley has been managed in some respects as a human-environmental system (e.g., in 2011 flood operations; Allison et al., 2013). The Louisiana 2012 Coastal Master Plan likewise supports some dimensions of systems-wide management.

The current generation of integrative water and environmental modeling encompasses these ecological, risk, and behavioral processes more fully (e.g., Loucks and Van Beek, 2005; Simonovic, 2009). The next generation of studies likely will advance by incorporating human settlement processes, livelihood strategies, and possibly cultural and technological change. This

TABLE 2-4 Deltaic Population and Areas

Delta	Population at risk	% delta population at risk	% delta area potentially lost
Amazon	69,300	1.89	2.45
Bengal	3,430,000	1.78	5.50
Burdekin	24	0.28	1.33
Chao Phraya	12,300	0.01	0.34
Colorado	544	0.11	3.35
Danube	3150	2.56	4.18
Dnepr	1300	5.60	7.31
Ebro	470	2.00	2.19
Godavari	453,000	16.2	22.5
Grijalva	26,700	1.76	5.59
Hong (Red)	70,500	0.85	0.95
Indus	7200	0.79	2.73
Irrawaddy	866	0.01	0.03
Krishna	16,900	1.92	3.42
Lena	0	0	1.07
Mackenzie	0	0	5.43
Magdalena	1980	0.07	1.97
Mahakam	64,800	7.06	6.29
Mahanadi	101,900	1.73	3.51
Mekong	1,910,000	6.51	5.82
Mississippi	480,000	18.5	19.9
Moulouya	7470	6.49	6.46
Niger	59,000	0.69	3.26
Nile	1,300,000	1.53	2.08
Orinoco	34,200	21.3	21.0
Parana	267	0.04	0.53
Po	312	0.65	0.80
Rhine	43,900	2.04	4.00
Rhone	2590	2.63	5.56
Rio Grande	3930	0.13	1.69
Sao Francisco	5720	9.04	11.23
Sebou	7180	4.36	3.30
Senegal	23,800	3.95	1.59
Shatt el Arab	54,300	4.45	3.34
Tana	392	7.25	5.68
Volta	6320	1.13	1.12
Yangtze	484,000	1.07	3.17
Yellow	3760	0.57	1.02
Yukon	31	2.06	1.98
Zhuijiang	25,500	0.20	0.39
World	8,710,000	2.0	4.9

NOTE: Distribution of the total population potentially impacted, percentage of delta population influenced, and the delta area impacted for each delta under baseline ESLR conditions extended from 2000 through 2050.
SOURCE: Ericson, Vörösmarty et al. (2006).

already is happening to some extent through interdisciplinary research with GIS platforms and coupled environmental and social models. It is also happening through community-based GIScience, citizen-science, and collaborative modeling as will be elaborated in later chapters. Not all systems inquiry involves formal quantitative modeling. For example, there is a valuable legacy of parish coastal zone planning in Louisiana (e.g., Sevier et al., 2000). There also are creative frontiers opening up in studies of "shrinking cities," such as New Orleans (e.g., Ryan, 2012; Zaninetti and Colten, 2012).

- **Each of the agents of change considered in this report has received substantial scientific attention, yet potentially entails numerous unmet research needs. These individual agents of change are highly interdependent. It thus is not possible to fully explain complex problems (e.g., coastal land loss in Louisiana) through research on individual agents alone. Nor is it possible to meaningfully advance integrated water and environmental management through a reductionist approach of the sort often adopted in some scientific investigations and projects, as compared with a systems approach.**
- **It therefore is important to articulate a "human-environmental systems approach," grounded in the Mississippi delta base case—and to use that systems approach to seek partial analogues with other large deltas in ways that inform, inspire, and challenge integrated water and environmental management in the lower Mississippi River delta.**

Promising International Analogues

This report's statement of task calls for it to address commonalities between the Mississippi River and other deltas of the world. By starting with a discussion of the lower Mississippi River delta, and the agents of change in the region, this regional setting represents a base case for comparison. In referring to some other river deltas around the world, the Mississippi River delta is situated in a comparative international context, and several potential international analogues are presented. There will be no perfect analogues; all are partial (i.e., useful in selective ways). The value of comparative assessments is not limited to "successes" only. Suboptimal or flawed examples also offer learning opportunities, as do contrasts between the Mississippi River and other deltas.

Venezuela's Orinoco River, for example, provides an example of a delta or lower river comparison for the Mississippi in that it offers some contrasts with the Mississippi. The lower Orinoco floodplain and delta are sparsely populated and lack significant infrastructure, although petroleum development is planned. The river maintains a delta that is relatively small compared to the Orinoco discharge; the Mississippi discharge is half that of the Orinoco, but the Orinoco delta is less than half as large as the Mississippi delta (Syvitski et al., 2009). The delta's modest dimensions are explained at least in part by the small amount of sediment per unit volume in waters of the Orinoco (Lewis and Saunders 1989), which are the lowest of all large global nontributary rivers that reach the ocean. Nutrient concentrations in Orinoco waters are extremely low, as they are unenriched by land use or waste disposal processes. Water passes through the delta mainly by way of two principal distributaries. Many other distributaries exist but are small. Low sediment load per unit volume stabilizes the path of water through the two main distributaries.

The main analogues identified for comparison in this chapter and discussed later in the report include the Rhine (flooding, hazards, management); Danube (environmental management); Mekong (sediment, hazards, fisheries); Ganges-Brahmaputra (flooding; hazards; fisheries); Irrawaddy (hazards, biodiversity); Niger (oil and gas development); and the three major deltas in China (Yellow [Huanghe], Yangtze [Changjiang], and Pearl [Zhujiang]—sediment, urbanization, management). In seeking to inform decision making via international comparisons, it is important to survey a range of possible analogues that offer different lessons and innovations.

- **Large deltas of the world vary so greatly that international comparison focused solely on one or a few agents of change are not likely to provide comparisons robust enough to advance the theory and practice of integrated water and environmental resources management in the Mississippi River delta.**
- **Research on deltaic "analogues" focuses first on a base case, which in this study is the Mississippi River delta. It then may examine specific agents of change by constructing problem-driven partial international analogies, set within a systems framework, to help advance the theory and practice of integrated water and environmental management.**

3

Strategic Research for Integrated Water and Environmental Management

The previous chapter provides the rationale for a systems approach to deltaic research, and for integrated water and environmental management. This chapter builds upon these themes with a set of strategic research opportunities that could be part of a systems framework. The identified research needs are broad, especially in comparison with specific disciplinary topics. They reflect a strategy based on initial research that focuses on large-scale, near-term questions in the Mississippi River delta region, and proceeds toward longer-term studies, including comparative international research. As the Water Institute plans to use this report in part for "strategic planning" purposes, it may find it useful to examine recent research on strategic planning and schools of strategy formation (e.g., Mintzberg, 2007).

Some of the research opportunities identified below might be pursued separately, or they might be combined into a single broader study. For example, the value of preparing a synthesis of research on the Mississippi River delta is discussed; and also, conducting a Condition of the Delta assessment that would yield a baseline study for restoration experiments. For clarity, they are presented separately below; but it may also be possible to combine them.

A RESEARCH SYNTHESIS

Past research in the lower Mississippi River and its delta is extensive. It includes studies of hydrology, sediment dynamics and erosion, effects of severe storms, coastal effects of oil spills, ecological conditions in freshwater and tidal marshes, commercial fisheries, infrastructure, human demographic processes, and the built environment (cf., CPRA, 2012 appendices; Lower Mississippi Region Comprehensive Study Coordinating Committee, 1974-1975; and State of the Coast conference proceedings, 2010, 2012).

There apparently is no synthetic overview of the current state of knowledge on this broad range of topics, which link the lower Mississippi River valley with the coastal zone. The lack of a comprehensive synthesis inhibits broad systemic understanding of the research landscape, knowledge gaps, general findings and conclusions, key uncertainties, and related error bands or confidence intervals.

A vast body of relevant water resources and related research has been conducted over past decades in the lower Mississippi River region, and for the Louisiana 2012 Coastal Master Plan (e.g., Mesehle et al., 2012a). A synthesis of these large bodies of research could present broadly useful basic information, and interpretations of hypotheses that have been tested or that currently may be either widely accepted or controversial. A synthesis document of this type could promote a sense of perspective and community among research organizations in the delta. The synthesis could be revised periodically (e.g., 5-year intervals), and could be supported by a modern archiving system designed around science and engineering programs and activities relevant to the delta environment.

Similarly, although enormous bodies of research on the Mississippi River delta have been undertaken, there does not appear to be a comprehensive "institutional map" of that research (i.e., a systematic chart of research organizations, major projects, archival collections, etc.). Likewise, there apparently have not been detailed historical assessments of how the Mississippi River delta has been compared with other deltas around the world (although see Roberts and Coleman, 2003, on the history of the LSU Coastal Studies Institute). As large-scale research on restoration projects unfolds, a research synthesis, institutional map, and historical review would have immediate as well as long-term value.

- **Preparation of a Mississippi River delta Research Synthesis report offers a research opportunity for the Water Institute. This report could, for example, include an institutional map of major research programs and resources. It would require a robust geographic definition of the delta, a historical review of Mississippi River delta research and development, and a perspective on the international context for research.**

CONDITION OF THE DELTA ASSESSMENT

One challenge for understanding and predicting the behavior of a complex system is establishing a baseline for comparison. A baseline should be an integrated dataset of the state of the system over some relatively short time that can be considered a "snapshot" of the system. For a system such as the lower Mississippi River delta that is studied by scientists from a variety of disciplines, prior research projects have been conducted using baselines developed at different times or in different locations that are relevant to the specific hypothesis being tested. Without a common time-space baseline, it will be difficult for future research to examine quantitatively the cross-disciplinary effects associated with complex interactions.

Biennial State of the Coast conferences in Louisiana result in a compilation of many valuable papers on deltaic science but do not purport to provide an integrated synthesis or baseline.[1] The Louisiana 2012 Coastal Master Plan appendices compiled datasets for modeling and screening, and a variety of spatial data platforms have been created over time. Examples include Atlas—the Louisiana Statewide GIS; CLARIS (coastal resource information system); CLEAR (coastal ecosystem assessment); LAGIC (Louisiana Geographic Information Center); and SONRIS (natural resources including oil and gas). Establishing a State of the Delta assessment across data platforms on water, landscape, and human factors, and supported by short-term field data collection to fill strategic gaps, could provide a valuable baseline for long-term research.

This baseline could be described as a *Condition of the Delta Study*. Such a study would entail significant collaboration among the many research institutes and investigators who work in the delta (as well as significant external funding). The study could employ existing environmental monitoring instruments for use across broad swaths of the delta for a common time period.

An expected advantage of a Condition of the Delta Assessment in the early years of the Water Institute's development is that it will require developing communication channels and dialogue across the research institutions working in the region. Scientists from disparate disciplines can be convened, which could provide connections that lead to extramural funding from interdisciplinary programs.

An international analogue for a Condition of the Delta study has been prepared for the Rhine delta (Deltares, 2009). Other international deltas such as the Mekong have also been the subject of database development and edited research volumes, but again this stops short of providing a coordinated baseline assessment (Renaud and Kuenzer, 2012; cf. Deltares,

[1] For more information, see: http://www.stateofthecoast.org.

2011a). However, the WISDOM: German-Vietnamese collaboration on the Mekong delta deserves study for its well-structured archiving of interdisciplinary sources that encompass hydrologic and ecological processes, cartographic data layers, time series data, livelihood studies, and information on landscape formation processes.[2]

- **A comprehensive State of the Delta baseline for data across water, landscape, and human factors has not been established. As such, this is a research gap and a research opportunity for the Water Institute and allied organizations.**

- **The Water Institute could provide the central motivation and coordinating effort for the promising research opportunity of developing a Condition of the Delta assessment. This ideally would be conducted with broad collaboration among stakeholders and scientists working in the Delta.**

RESEARCH DESIGN FOR DIVERSION PROJECTS

The State of Louisiana's 2012 Coastal Master Plan has committed to river diversions and other natural infrastructure restoration projects that are likely to be controversial from scientific and public policy perspectives (e.g., see New Orleans Times-Picayune, 2013). Such projects inherently involve activities that might simultaneously be considered beneficial by one party and harmful by another. Furthermore, uncertainties associated with understanding the interactions among elements of such a complex system ensure that not all consequences and outcomes of these projects can be forecast with precision (see Kearney et al., 2011, and Turner, 1987 and 2011). This makes the outcomes of these projects inherently uncertain (Mesehle et al., 2012b). This setting presents an opportunity for the Water Institute to advance science that supports adaptive management for large-scale ecosystem restoration. Similar future research opportunities for the Water Institute will entail further collaboration and agreement with the Louisiana CPRA.

- **The Water Institute could identify key decision-relevant uncertainties in the planned diversion projects, propose building experiments into project and policy designs, and contribute to scientific monitoring of results.**

[2] See http://www.wisdom.caf.dlr.de/.

Research for Adaptive Management

Adaptive management in the most general sense means monitoring hypothesized effects of actions, projects, and programs to determine whether the outcomes materialize as expected. Information on those outcomes then is used to recon or adjust the design and operation of a project, and to guide design and operation of future similar projects. A 2004 NRC committee issued a report on adaptive management for the U.S. Army Corps of Engineers. That report noted some fundamental concepts of the approach, minimal areas of agreement for stakeholders, and expectations from the concept:

> Participants in adaptive management programs must at least agree upon key research questions or lines of inquiry to be pursued by an adaptive approach (Lee, 1999). Some agreement on larger objectives could help better define program direction; but if full agreement on ecosystem management goals exists (an unusual condition), there would be a reduced need for adaptive approaches. Adaptive management is a means for bounding and addressing disputes and differences. As adaptive management proceeds, not only will ecosystem understanding by participants increase, but social and political preferences are likely to evolve, and environmental and social surprises may occur. Key questions, paths of inquiry, and programmatic objectives should be regularly reviewed in an iterative process to help participants maintain a focus on objectives and appropriate revisions to them. (NRC, 2004, p. 24)

There is today a rich literature on the theory and practice of adaptive management. Although not possible to comprehensively review and critique here, adaptive management activities often are viewed as ranging from active (or anticipatory), to passive (or reflective), forms. The active form has more controlled and explicit experimental and learning objectives, while a more passive approach adjusts to results of actions that have fewer controls and less explicit learning aims and methods. Pure forms of active adaptive management rarely are possible because of a variety of factors, including limited funding for model development and related scientific research, limits for experimental decisions and regimes, and differing stakeholder preferences and opinion.

Despite the associated challenges, implementation of the Master Plan projects that will soon be constructed, and the policies that are being formulated, offer some excellent opportunities for structured adaptive management (cf., brief chapter in CPRA, 2012). Given the size and many complexities of lower Mississippi River hydrology and ecology, and related social and economic systems, some management decisions will need to be adjusted and improved in the future. Despite extensive work to date, the magnitude of effects for the planned Delta restoration projects on nutrient levels, marsh creation, and areal integrity of wetlands areas remains uncertain—indeed, one might say that there are mainly hypotheses, which will be tested by the projects. The Water Institute is not an action agency for planning or executing integrated water and environmental management decisions; rather, it seeks to provide scientific support and analysis for policy makers.

Issues of research design, large-scale experiments, and sampling and monitoring protocols are well illustrated by adaptive management programs in other regions of the United States and Europe. For example, the Grand Canyon Monitoring and Research Center convened peer review panels to define measurement protocols for multiple-experiment research programs on sediment transport, ecological dynamics, and cultural heritage impact assessment (NRC, 1996, 1999). Several decadal experiments with adaptive management in Europe also offer insights into strategic research approaches (e.g., Vermaat et al., 2005 on European coasts; and Deltares, 2012 on the relevance of Netherlands and U.S. programs for East Asia).

Adaptive management in the Mississippi River delta could benefit by surveying experience in the United States. and internationally. As in the Grand Canyon, it could identify common research design and monitoring protocols for restoration project effects, interactions, and performance (Paola et al., 2011). It could anticipate the otherwise confounding effects of extreme events such as hurricanes or severe droughts, ecological "surprises," and social change by incorporating them as contingencies in research design. Establishment of a "quick response" grant program could collect perishable data to better understand the earliest processes of human adjustment and environmental change (Natural Hazards Center, 2013).

- **Design of scientific research to support adaptive management of large-scale ecosystem restoration projects is a significant research opportunity in the Mississippi River delta context.**
- **As some uncertainties will unfold during the course of diversion experiments, a "quick response" research grant program for internal and external applicants could facilitate rapid collection of perishable data in the event of environmental surprises and hazards.**

LONG-TERM MONITORING

Long-term monitoring is traditionally the purview of government agencies providing the public information on topics such as environmental changes and trends, public safety, and economic indicators. Data collection for weather, rainfall, streamflow, tides, and water quality variables is a well-established and uncontroversial task of government because of the recognized value of these data to commerce and the public.

A robust adaptive management program needs data collection aimed at proving/disproving the effectiveness of the restoration efforts, and responding effectively to experimental outcomes. Sustained, multidecadal data collection to support a regional-scale adaptive management program would be costly, and perhaps an inappropriate role for the Water Institute and its interests in strategic research. Basic data collection of environmental variables likely is a more appropriate role for federal (e.g., U.S. Geological Survey) and state (Louisiana Department of Environmental Quality). At the same time, there may be opportunities to review ongoing (federal and state) monitoring programs, and provide advice for improvement.

- **A research opportunity in complex deltaic systems is to help identify emerging decision-relevant variables and time scales, and then to propose cost-effective adjustments in monitoring programs, including new data sources, methods, and technologies.**

RESEARCH ON SETTLEMENT, LAND USE, AND LANDSCAPE CHANGE

The role of land use is critically important for management of deltas but has been addressed in limited ways in water management. Examples of important implications of problematic land use are increased exposure of populations to flood risk, and compromising of floodways' functionality through settlement and development.

Many human settlements historically have located along rivers. Despite threats from periodic flooding, riverside settlements have ready access to water supply, fisheries, and navigation opportunities. Early settlers in the United States understood the importance of subtle topographic differences, and exploited natural levees along large, meandering rivers (Kondolf and Piégay, 2010). Natural levees form when floodwaters overflow the channel, their velocity slows, and coarser sediments in suspension settle out, building up a berm of sand along the channel margin that slopes gently downward away from the channel into the floodplain. Along the Sacramento River, for example, early settlements were restricted to the natural levee (Kelley, 1989). Likewise, in New Orleans, the older neighborhoods of the French Quarter and Garden District were built on the higher ground of the natural levee of the Mississippi. Away from the river, low-lying floodplain areas were inundated annually and recognized as ill-suited for human settlement. The advent of powerful pumps in the twentieth century made it possible for these low-lying lands to be occupied, but as their soils were exposed to the atmosphere, vast areas subsided below sea level (Campanella, 2002). These fluvial landforms were manifest in the pattern of inundation depths during Hurricane Katrina, with natural levees (of the modern river and ancient distributary channels such as the Metarie-Gentilly Ridge) either dry or only shallowly inundated, while many floodplain areas were flooded to depths greater than 4 meters.

By comparison, along the lower Mekong River in Cambodia, settlements (often built on stilts) and permanent agriculture (e.g., fruit trees) are located on natural levees, with back-swamp areas used for annual crops (Campbell, 2009). In Bangladesh, artificial flood-control levees have typically failed to control floods, but ironically serve as "high ground" onto which residents take refuge during inundations (Sklar, 1992). Where no high ground is available, people often have taken refuge from floods by migrating from flood-prone areas during the wet season or building elevated structures above anticipated flood levels. In Dadun, a "water village" of the Pearl River Delta in China, the flood of 1962 inspired many residents to build second and third stories on their houses in anticipation of future floods (Bosselmann et al., 2010).

However, with the construction of flood control levees in many of these deltaic regions, the perception that low-lying lands are protected from flooding can encourage development in the "protected" areas behind the levees (White 1945, 1974). All levees provide protection only up to a specified design flood, typically determined based on assessment of risks and costs of various "levels of protection." In the Netherlands, levees around urban areas are typically built to protect against river floods with return intervals of 1,250 years, while delta and coastal levees are designed to provide 4,000- to 10,000-year flood protection (Jonkman et al., 2008). In the United States, the National Flood Insurance Program uses the 100-year flood (the flood with a 1 percent chance of occurring in any given year) to determine the "floodplain," and as a consequence, levees are typically constructed to provide protection from the 100-year flood (Kondolf and Podolak, 2013). However, lands behind such levees remain vulnerable to inundation by larger floods, and the "residual risk." Without levees, the floodplain would be subject to "nuisance flooding" every few years, reminding decision makers and the public that the lands are prone to flooding. However, residents of lands "protected" by 100-year levees often do not fully perceive their residual risk of flooding (Ludy and Kondolf, 2012). By "filtering out" frequent smaller floods, levees may turn a frequently occurring natural hazard, to which society may be relatively well adapted, into an infrequent natural hazard, to which society becomes more vulnerable (Kondolf and Podolak, 2013).

Levees encourage development in floodplains and thereby expose more people and structures to flood damage, which ultimately exacerbates the damages caused by larger floods (Werner and McNamara, 2007). For example, floodplain inhabitants behind levees may perceive that they are fully protected. This may encourage development in fundamentally risky places, and/or discourage nonstructural measures such as raising buildings above the anticipated flood levels and improving warning and evacuation methods.

Moreover, because land-use decisions are taken at the level of local government, it is often difficult to enforce well-designed policies adopted at the national or state level, the level at which integrated water management is commonly conceived and implemented. Local governments often are motivated strongly to approve new developments in order to benefit from development fees and tax revenues, and local officials may not understand (or choose not to recognize) the real long-term flood risk to development in low-lying lands (Eisenstein et al., 2007). For this reason, empirical research on patterns and trends in floodplain occupance has continuing importance.

Similar problems arise with lands within designated floodways, for which the federal government holds flowage easements. Local governments may issue building permits, or fail to stop unpermitted construction, within the designated floodways. The results can be encroachment of urbanization into the floodways such that flood managers become reluctant to utilize these essential components of the flood management system out of fear of political "fallout" from damaging the encroached developments.

Given the reality of many crucial land-water relationships and linkages, it is essential to coordinate land occupancy issues with management of water to encourage wise economic investments, ensure public safety, and promote long-term ecological protection or restoration. The reality, however, is that given traditional lines of authority and decision making, existing institutions in the Mississippi Delta are unlikely to want to address the issue directly.

- **There are research opportunities in the lower Mississippi River delta for analyzing changing land use and building patterns and trends, and for explaining how projects and policies can influence those trends in ways that advance or constrain the paths and prospects for integrated water and environmental management.**

DELTAIC ZONATION

River deltas are complex, adaptive systems that evolve constantly in response to changing environmental forces. Medium-term (decadal to century) changes in delta geomorphology occur in response to alterations in river flow and sediment load and to local tectonics. Long-term (thousands to hundreds of thousands of years) delta dynamics are linked to glacial-interglacial cycles. Delta stability reflects a delicate and dynamic balance between incoming sediment load, which grows and stabilizes the delta, versus subsidence, sea-level rise, and erosion, which degrade the delta.

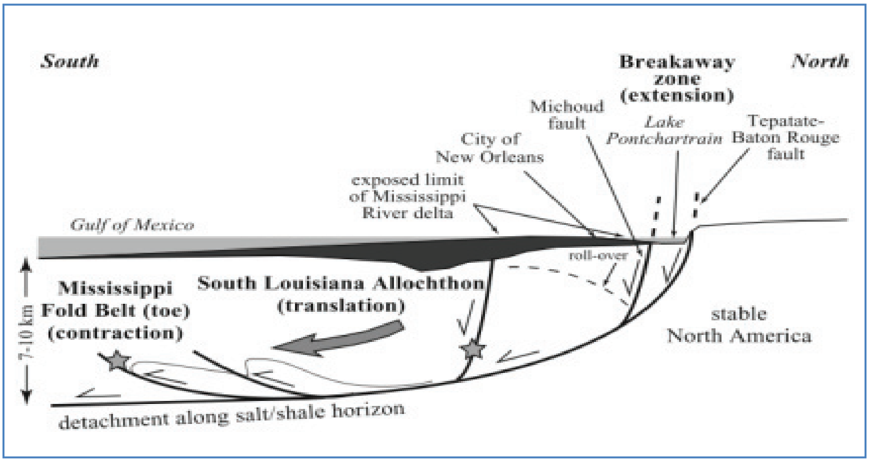

FIGURE 3-1 The South Louisiana Allochthon (large block of rock moved from its original site).
SOURCE: Dokka et al., 2006.

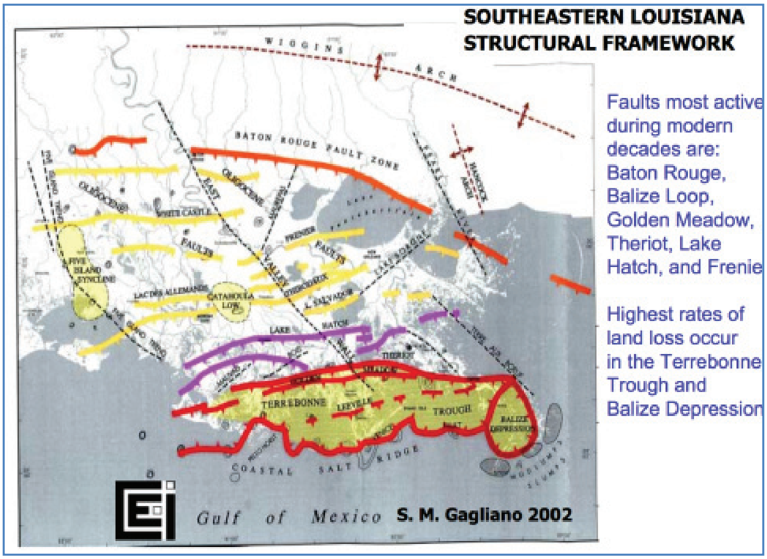

FIGURE 3-2 Fault zones in the Mississippi River delta.
SOURCE: Gagliano, 2002.

Tectonic processes exert a major control on delta stability in the Mississippi River Delta. Since 1930, over 600 square miles of land area south of the Golden Meadows fault zone have been converted into open water habitat by slumping (Gagliano, 2005). The cross-section in Figure 3-1 depicts the structural features and processes, while the map in Figure 3-2 delineates their rough alignment in the lower delta.

The precise fault alignments are not always clear, but much of the region south of this fault zone is inherently unstable, and land loss rates continue at a rapid pace. Although oil and gas and groundwater extraction contribute to land loss in this area, tectonics is a primary driver, and as such it is critical that tectonic stability be considered in regional planning processes.

- **More detailed mapping of major geologic areas of relative stability, major land loss vulnerability, and land-building potential could help guide research on diversions and coastal protection project performance.**

4

Science-Policy Analysis: An Emerging Research Frontier

This chapter focuses on the topic of integrated water and environmental management, and linkages between scientific research and policy analysis. The Water Institute has not emphasized its role in science-policy analysis, but insofar as it conducts strategic research that is part of a science-policy process, it will benefit by analyzing the policy context of its work, and along with other participants, help shape science-policy research.

Policy analysis is an established, specialized field of water and environmental research, as is science-policy analysis that rigorously examines the roles and uses of science in policy analysis, and the design and performance of science-policy experiments (as in adaptive management discussed in chapter 3) (Chenoweth, 2012). Previous approaches to IWRM in the United States and internationally are relevant to policy analysis, as is research that builds upon Louisiana's 2012 Coastal Master Plan. Science-policy research topics discussed in this chapter are (1) *Research Components of IWRM: An Example from the Netherlands*, which includes full system description, computational framework, and governance; and (2) *Science-Policy Research for Master Planning in Louisiana*, which includes policy analysis; collaborative modeling, citizen science, and decision support systems.

RESEARCH COMPONENTS OF IWRM: AN EXAMPLE FROM THE NETHERLANDS

As explained in Chapter 1, Integrated Water Resource Management strives to view and manage water systems from a comprehensive point of view. This section offers a perspective on the use of IWRM in the

Netherlands. The Dutch experience may be relevant to the Water Institute given the latter's intent to employ IWRM concepts, and the lengthy and sophisticated experience in the Netherlands in implementing this multidisciplinary concept.

The ongoing "Delta Programme" encompasses three broad components of water systems in the Netherlands:)1) the natural resource system (NRS), (2) socioeconomic systems (SES), and (3) administrative and institutional systems (AIS). When considering these components in an integrated manner, Dutch planners and decision makers seek to support socioeconomic development of the region, particularly navigation and agriculture, to provide flood protection, and to improve environmental quality.

Although IWRM strives to deal with all water issues in an integrated way, this is not completely followed in the Netherlands. The prime goals of the Netherlands Delta Programme are flood control and drought management. Water quality and ecology are more fully addressed under the regional European Water Framework Directive. Both programs evaluate projects from an integrated perspective that considers impacts across programs. The Netherlands experience with IWRM underscores the following components that are elaborated below:

- *Description of the full system*, including physical, socioeconomic, and institutional processes (NRS, SES, and AIS) and interactions among them.
- *A computational framework* of models and databases that represent knowledge of the system and enables quantification of impacts from proposed actions.
- *A governance system* that involves close cooperation among stakeholders, scientists, and decision makers.

Full System Description

Integrated water resources management practices in the Netherlands entails full assessment of human and environmental systems, which includes description of the following:

- Natural resources systems (NRS)—environmental processes, development alternatives, and potential impacts
- Socioeconomic systems (SES)—water uses and their economic value, water demand, economic trends, and planned developments
- Administrative and institutional systems (AIS)—stakeholders and their interests in the water systems, governance structures, and legal setting

- Interlinkages among these components and benefits from improved water management
- Development of scenarios that capture external uncertainties that might have an impact on the system (e.g., climate change, demographic trends, and soci-economic development; see Figure 4-1).

For the lower Mississippi River, an assessment of this sort ideally would cover the entire delta region, and hence would include urban and rural areas, navigation, and industrial development. From the Netherlands perspective, it would also ideally be coordinated with IWRM at the basinwide and national water policy scales.

Computational Framework

A computational framework in the Dutch context to support integrated water management includes models and databases that describe various components of the system, in particular the natural resources and socioeconomic systems (often described as a decision support system). The computational framework in integrated water management often differs from models used by environmental scientists and water managers, particularly with respect to the role of models (e.g., for interactive communication as well as scientific explanation and simulation). Figure 4-2 illustrates the development of the "delta model" used in the Netherlands.

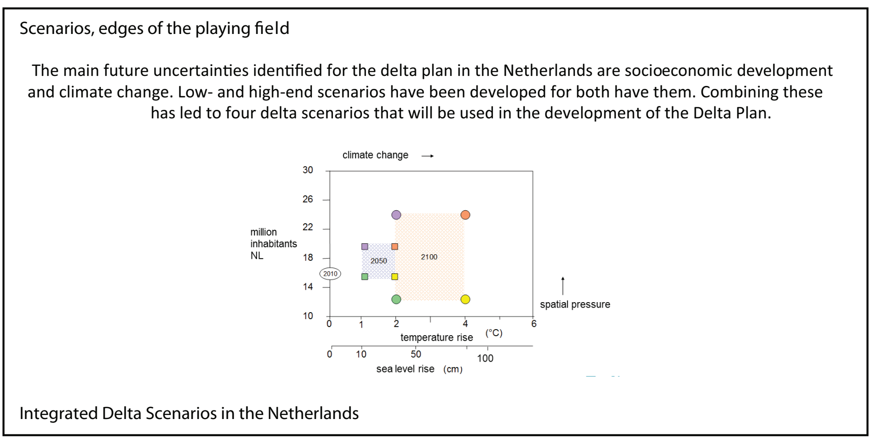

FIGURE 4-1 Integrated delta scenarios in the Netherlands.
SOURCE: Bruggeman et al., 2011.

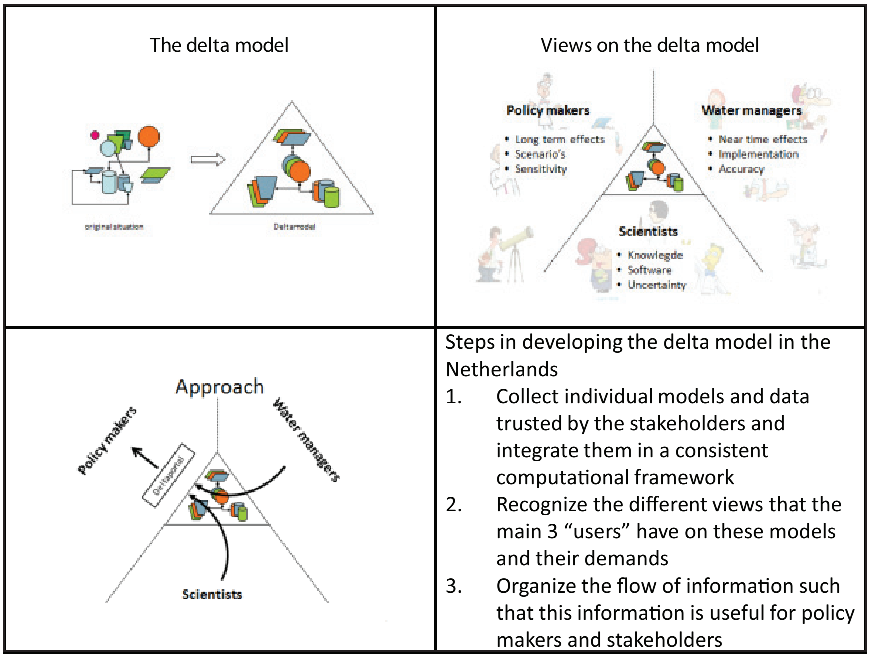

FIGURE 4-2 Schematic diagram of the delta model.
SOURCE: Kroon and Ruijgh, 2012; van Beek, 2013.

The computational framework for IWRM analysis is a consensus-building model. Users need to trust the models and input data. Certain components may originate from or be developed with stakeholders (e.g., the socioeconomic system models). As full models are complicated and computationally heavy, simpler models are developed to produce reliable results for IWRM planning purposes, while recommendations are checked with full models.

Governance in Integrated Water Management

Governance is part of the full system description discussed above, and it is an essential component of IWRM (GWP, 2008). Governance research has been a major focus of international water management research over the past decade, shaped in Europe by the Water Framework Directive (Reinhard and Folmer, 2009; Timmerman et al., 2008). Recent Dutch studies of U.S. shorefront and flood hazards management have also compared governance approaches (Rijkswaterstaat, 2005; Wesselink, 2007). Governance research was identified as an unmet research need for the Mississippi River delta in the Delta Alliance's comparative study (Bucks et al., 2010).

According to the Global Water Partnership (GWP, 2008, pp. 8-9), the main roles and functions of water governance are to

- "ensure that water resources can provide the range of water products and services required for social and economic development and environmental sustainability;
- mitigate or adapt to externalities that include water-related hazards, waterborne diseases, pollution, and other effects that particular water uses and users can impose on others within a physically independent water and land system;
- allocate water resources and services, along with the associated financial and human capital, in an efficient, equitable and environmentally sustainable manner."

The roles of governance in deltas are particularly important because of their environmental complexities, resource uses, and trade-offs (GWP, 2003, 2008). Governance systems ideally involve the full array of stakeholders in decision making, and provide ready access to scientific information used in decision making (GWP, 2008). Successful implementation of plans is possible when there is sufficient consensus among the stakeholders.

Pathway Analysis in IWRM

The Dutch Delta Programme uses an adaptive approach to meet safety and socioeconomic targets, while remaining flexible as to how and when to implement management interventions. One challenge is to make this adaptive approach operational, and the novel approach adopted in the Netherlands involves adaptation pathway analysis as an alternative to traditional "end-point" scenarios.

This approach identifies thresholds to indicate when a policy starts to perform unacceptably, and what alternative adaptation pathways and policy actions are available to achieve social and environmental objectives (Figure 4-3). The illustrative scorecard in Figure 4-3 displays nine climate adaptation pathways (Haasnoot et al., 2013). The scorecard shows that the Current Policy fails to meet its targets after 4 years, at which point there are four alternative actions A through D. Actions A and D achieve their targets for the next 100 years under all climate scenarios. If Action B is chosen, by comparison, a threshold ("tipping point") is reached within about 5 years, at which point a shift is needed to one of the three other options. This type of dynamic pathway analysis is helping make adaptive delta management operational in the Netherlands.

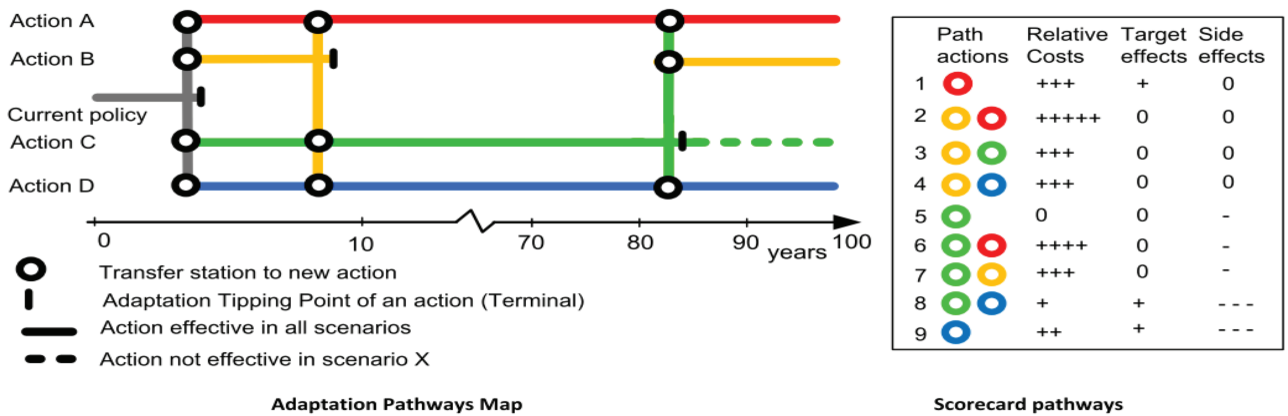

FIGURE 4-3 Dutch water planning schematic of water development scenarios, and policy choices.
SOURCE: Haasnoot et al., 2013.

SCIENCE-POLICY RESEARCH FOR MASTER PLANNING IN LOUISIANA

The Dutch situation and experience are often cited as an analogue for storm protection activities and structure for Louisiana and the U.S. Gulf Coast. Dutch experts have been consulted frequently about strategies to address problems such as storm hazards, land loss, and socioeconomic stresses in Louisiana and elsewhere. The Dutch approach to delta management has been built around construction of massive coastal defenses (dikes) at the outer perimeter, with large floodgates and locks controlling the aquatic environments within this perimeter. Although there may be much to be emulated in that nation's systematic approach to planning and design, there are some significant contrasts with coastal Louisiana.

First, the Netherlands lies on a stable geological foundation; rates of subsidence are much lower than in coastal Louisiana. Dikes sink slowly not only because of low rates of regional subsidence but also because underlying sediments are not readily compressed. Further, maximum storm surges caused by tropical cyclones that affect the Louisiana coast exceed those caused by North Sea winter storms that threaten the Netherlands.

For centuries the Dutch have been reclaiming land from the sea primarily for human settlement and not some other purpose (e.g., ecosystem restoration). A large portion of the densely populated Netherlands thus is at risk from river flooding or storm surges. National policies and budgets reflect delta protection as a dominant national priority. This degree of national-level priority is not likely to apply to the Mississippi River delta, its many values to local residents notwithstanding. Despite national attention devoted to the Gulf coastline, national and state policy appears to have established that the costs (financial and environmental) of a "Dutch solution" are not justified across all of Louisiana, which has a coastline three times as long as that of the Netherlands. Instead, for areas of dispersed human settlement there is increased interest (as reflected in the recent Master Plan) in reducing exposure and vulnerability through actions such as elevated buildings, and managed retreat as addressed in part in the Louisiana 2012 Coastal Master Plan.

- **There is a growing body of international research on science-policy studies of deltaic vulnerability and sustainability. At the same time, there are expanding opportunities for rigorous comparative research on science-policy programs in other regions, such as the Netherlands, for integrated water and environmental management in the Mississippi River delta.**

Building on the Louisiana 2012 Coastal Master Plan

Notwithstanding these differences between the Netherlands and the Mississippi delta, there is much to learn from Dutch and other international experience. The likelihood of a major new infusion of funding for river diversions, barrier island restoration, and managed retreat may soon be on a scale analogous to coastal investment in the Netherlands.[1] In its own way, Louisiana represents a unique-in-the world learning opportunity for science-policy research that contributes to planning, designing, evaluating, and integrating “soft” and “hard” engineering interventions at the coastal margins. Louisiana’s 2012 Coastal Master Plan is the core policy document for such research.

Research on Interactions among Multiple Projects

The Louisiana 2012 Coastal Master Plan evaluated hundreds of projects of different types, and it acknowledges that it did a limited analysis of “multiple projects at the same time to see how the projects within the master plan interacted” (CPRA, 2012, p. 89). Interactions among multiple projects entail interesting and important scientific research issues, including the following:

- Interactions between structural projects and nonstructural programs
- Synergies, complementarities, overlaps, and conflicts
- Unexpected consequences, either positive or negative
- Relative benefits of a large-scale centralized project compared with a distributed set of small-scale projects
- Relationships between strategic and tactical measures for hazards mitigation

There is thus an excellent opportunity for the Water Institute and others to build a research program around the multiple types of interaction effects among delta projects and policies.

- **There is an excellent opportunity for the Water Institute to build a research program around multiple interacting types of restoration projects and policies.**
- **There are also near- and medium-term research opportunities on the integration of storm protection structures with delta restoration projects that emphasize natural or green infrastructure. This inte-**

[1] In the wake of the 2010 Deepwater Horizon explosion and oil spill, tens of billions of dollars were directed to organizations such as the National Fish and Wildlife Federation (NFWF) for the express purpose of Gulf of Mexico ecological restoration. Some of these monies are likely to be used for restoration activities in the lower Mississippi River delta.

grated approach to research could encompass and contribute to the objectives of a vigorous energy and marine transportation economy, storm risk reduction, commercial fisheries, recreational opportunities, and a healthy coastal ecosystem.

Research on Science-Policy "Decision Points" in the Master Plan

The Master Plan identified nine "decision points" based on a combination of science, policy, and public input, stating that it accomplished the following:

1. "Maximized community flood risk reduction and land building.
2. Assumed a $50 billion budget for planning purposes.
3. Used a balanced allocation of protection and restoration funds, taking into account that many restoration projects also serve to reduce flooding risk.
4. Divided investment equally between near- and long-term benefits.
5. Chose projects that are more robust should future coastal conditions track the less optimistic scenario.
6. Ensured that positive and negative effects of projects on ecosystem services were balanced and that negative effects are not significantly detrimental coast wide.
7. Focused marsh creation efforts on critical landforms, or key landscape features that provide both land building and storm surge reduction.
8. Incorporated projects in the master plan based on a realistic review of the limits of the analysis, implementation challenges, and variations in methods.
9. Adjusted projects based on local knowledge and stakeholder input where appropriate. The changes were principled responses to the feedback we received, grounded in science, and responsive to the needs of our coastal communities."

This is an important yet diverse mix of decisions, based on what the Master Plan describes as "reality checks" (CPRA, 2012, p. 108). These types of complex decision problems present opportunities to conduct research that builds upon them, and can help clarify the relationships among them. Some promising approaches are described below.

From Expert Driven Planning to Collaborative Decision Making

The Louisiana 2012 Coastal Master Plan process identified multiple objectives for the Gulf coast and then evaluated how combinations of investment and policy alternatives could meet those objectives over time. The resulting plan reflects tradeoffs among objectives. In this sense the Master Plan is an impressive example of integrated water planning for the benefit of agency decision making. In addition, the planning process, which involved extensive outreach, was also likely useful for gaining public understanding and support, and the Master Plan process engaged stakeholders through public hearings and workshop discussions. However, there were claims that stakeholders were not always fully engaged in the analytical modeling that led to the recommendations in the plan. Further, some principal users of the coast (e.g. marine transport and energy extraction) may not have engaged as actively as others in the Master Plan development process.

Conflicts among stakeholders over acceptable tradeoffs and preferred alternatives are to be expected in any planning process. These conflicts can be categorized as analytical disagreements (analytical conflict), in the way that benefits and costs are distributed (interest conflict), and in disagreements over the highest and best use for coastal resources (value conflict; see NRC, 2011b).

A substantive stakeholder engagement process that integrates technical analysis with stakeholder participation can inform and moderate such conflicts and negotiate agreements (Islam and Susskind, 2012). The purpose of a substantive engagement process can be limited to reaching agreement on the "facts of a situation" (joint fact finding) in order to reduce analytical conflict. Analytical conflict might be resolved, but a more ambitious purpose of engagement is to reach agreement about acceptable tradeoffs, as well as economic and environmental mitigation, in order to reduce value and interest conflict. The more ambitious purpose will be advanced if stakeholders are engaged in modeling of the system.

Whatever the source of conflict, the purpose of modeling is to make predictions of the consequences for the stakeholders' values and interests if a certain investment or policy is implemented. The credibility and acceptability of the predictions is advanced if the model platforms themselves have credibility and accessibility, and are not seen as "black boxes." Ideally, predictions are made through technical models that are vetted, and perhaps developed with stakeholder participation. This has been termed "collaborative modeling," "shared vision planning," "computer aided dispute resolution," and "computer aided negotiation." The U.S. Army Corps of Engineers has extensive experience in developing and applying the "shared vision planning" model, and has worked with stakeholder groups on many national and international water management issues, including the U.S. Great Lakes and Colorado River Basin (USACE, 2013b). The State of Louisiana worked with RAND in the use of decision-support modeling in the preparation of the state's 2012 Master Plan (Groves et al., 2013).

The case for substantive stakeholder and multiagency engagement in planning and decision making is well documented, as are the limits such involvement can place on expeditious decision making. Therefore, the focus of the engagement needs to be carefully considered. The focus can be narrow. For example, the focus can be on a single user group such as the marine transportation sector, on a particular location (a region or a community), or on a single project such as a diversion at a specific location. Also, the focus may be on a single question, such as the effect of nutrient concentrations on marsh habitat, or the effect of increased flood insurance premiums on location and retreat decisions for households. Alternatively, the focus may be on the broadest scale—the system—and thus inclusive of multiple purposes, multiple locations, and multiple projects.

Because of the large spatial scale, complexity, and long time horizon for planning and implementation, there may be successive rounds of planning as new projects and policies are advanced for consideration. This progression of planning offers opportunities to engage stakeholders in collaborative exercises, such as joint fact finding. Environmental design charrettes (intensive 1-day methods for generating design alternatives) and studios are also used to involve stakeholders in scenario generation and analysis in ways that can creatively expand the range of choice (Delta Alliance, 2010; Deltares, 2011b). Ideally, projects and policies will be evaluated through a system analysis that draws on (1) a baseline assessment, (2) knowledge gained from previous investments and (3) is open to benefiting from local knowledge.

Beyond joint fact finding, effective stakeholder engagement and resolution of all sources of conflict entails system modeling that is transparent to all decision makers. As in the Dutch context, such models will be of coarse resolution but will draw upon models of finer spatial and temporal scales for construction. They will be simple but not simplistic, in that they facilitate choices about general project designs, locations, and operations, rather than day-to-day operations or design refinements. They will be empirical, but where there are significant uncertainties in data or in relationships among variables in the model, characterization of the uncertainty and how it affects the results would be necessary.

Advanced analytic methods could help illustrate and analyze trade-offs among various water and related environmental uses. In turn, water users and decision makers may be able to use this information to promote better integration across related water sectors.

- **The Water Institute would have an excellent opportunity to promote, and lead, more advanced scientific stakeholder engagement in joint fact finding and modeling processes. A strong contribution to research on negotiation and collaborative modeling would entail some level of commitment by the Water Institute to develop the**

required professional skills to create and lead collaborative modeling procedures.

Citizen Science with Innovations in Information and Communications Technology

Citizen science conducted with modern telecommunications technologies can enhance socioenvironmental research. Citizen science involves participation and collaboration of members of the general public in scientific research, most often as unpaid volunteers. Such participatory efforts are designed to engage and educate the public about local and regional scientific issues. Designing collaborative ventures that engage members of the public to facilitate monitoring programs could be a useful function for the Water Institute. The Water Institute could take a leadership role in development of these types of digital information technology and management for the delta region. They could guide development of databases or technological tools that stimulate, advance, and empower citizen science efforts locally, regionally, and globally. Widespread availability of GPS-enabled smartphones allows citizens to provide georeferenced ecological data that could be valuable in filling in data gaps. Potential avenues of citizen-engagement at the Water Institute could include cross-Louisiana coastal community descriptions, water quality, and/or fishery catch "apps" to facilitate ecologically relevant data collection in the delta region; development of digital tools for tracking coastal erosion, marine debris and hazards; and coastal emergency response planning and relief (U.S. Department of Homeland Security, 2013). These efforts could promote scientific advancement, establish the Water Institute as a partner in local science efforts, and promote its reputation among Delta populations. Myriad social technology inventions, prototypes, and experiments are under way that can be screened by organizations devoted to this field (e.g., MIT Humanitarian Logistics, 2013).

- **The design of collaborative ventures that mobilize members of the public to facilitate monitoring programs is another research opportunity for the Water Institute. Part of this effort could include a leadership role for the Water Institute in developing digital information technology and management for the lower Mississippi River Delta.**
- **Hosting of international citizen-science workshops could also help identify innovations in other deltas that have relevance for the lower Mississippi, and ultimately help transfer knowledge to those regions.**

Decision Support Systems

Deltas are a complex "system of systems" characterized by interdependencies among systems of water resources, ecological habitats, infrastructure, energy, agriculture, and urban settlement. The Master Plan describes its planning tool as a decision support system (DSS). It helped integrate science, policy, and public input both to screen projects and to arrive at decision points. This chapter has surveyed a broad range of methods for supporting decision making, from IWRM in the Netherlands to research on Master Planning in Louisiana. The latter encompasses science-policy analyses, collaborative modeling, citizen-science, and new technologies. Taken together, this broad spectrum of approaches suggests a coordinated approach to DSS tools to help advance integrated water and environmental management in large deltaic regions.

One aim of a DSS is to bring science into decision making so as to develop a high-level understanding of science-policy relationships. Numerous models have been developed and validated for the delta by academic and consulting communities. Challenges exist for enhancing the appropriate use of multiple models in decision making. Another principle of DSS development is to involve practitioners and stakeholders from the early stages of data collection and model development.

In addition to qualitative methods of social inquiry, it is important to continue to develop quantitative social science models for demographic, socioeconomic, and equity analyses. Social research can shed light on decision behavior and behavior change, decision making under uncertainty, intertemporal preferences, consensus-building, and barriers and pathways to risk reduction. The current situation is characterized by a broad range of partial approaches to DSS in the Mississippi River delta, as in other deltas of the world. IWRM in the Netherlands presents one model for coordinating these tools.

- **Development of decision support system applications represents another science-policy research opportunity. This work could initially help support restoration project implementation, encourage integration of structural and nonstructural water and environmental management alternatives, and encourage participatory stakeholder and citizen-science programs.**

5

Research Coordination and Institute Planning

Preceding chapters have emphasized the role of collaboration in both domestic and international research. This chapter develops that theme in two ways. The first section of the chapter discusses opportunities and methods for research coordination among scientific research, industrial, agency, and civil society organizations. The second part of the chapter explores organizational options and strategies for advancing regional and international research.

RESEARCH COORDINATION

Relations with Research Institutes

Given its proximity to Louisiana State University in Baton Rouge, connections of Water Institute scientists with other academic institutions in the region, as well as applied and other federal research programs of the U.S. Army Corps of Engineers and U.S. Geological Survey, the Water Institute stands to play a role in helping create a community of scholars addressing important issues relevant to coastal Louisiana and the Mississippi River delta. There are many scientists, schools, and organizations carrying out research programs, but the benefits of collaboration and cross-fertilization of ideas have not yet been fully realized in the region. Despite many research groups at different institutions with vibrant, productive scientific exchanges, there seems to be a collective sense that more is possible. An illustrative example is the Louisiana Universities Marine Consortium (LUMCON), which was conceived of as an opportunity for all the universities and research labs in the region to collaborate on scientific research. Similarly, government agencies and research laboratories hold significant data sets and have expertise. The Water Institute could play an important role in fostering interchange of ideas and data among universities and research institutions active in the region.

Industry Relations

The Mississippi delta is heavily industrialized, so not surprisingly, there is a depth of expertise in the delta within the industries that operate here, notably the oil and gas industry, but also fishing, navigation, salt mining, dredging, construction, and other industries. Much of the industry data and expertise have been unavailable to other researchers. Although proprietary concerns will limit sharing of some of these data, some of it could potentially be shared to promote better understanding and management of the delta's resources. However, there have been few attempts by university, agency, or government scientists to reach out to industry for collaborations. There may be opportunities for the Water Institute to develop such links with industry (Box 5-1).

It is likely that many industry scientists would be open to exchange of ideas, and, as relationships are built over time, exchange of data. Industry scientists could stand to benefit from collaborations with academia as well, especially to the extent that they could influence research agendas toward issues of concern to industry. Moreover, there are likely important synergies that could develop, as for example, collaborative studies with environmental scientists could identify alternative disposal sites for dredge spoils that could actually be environmentally beneficial (and thus more easily permitted), and potentially less costly for the dredging industry.

Besides the wealth of subsurface data held by oil, gas, and salt industry scientists, the dredging industry could provide data on depths to which channels are dredged and volumes of spoils produced. Fishers could provide data on catches beyond those data already compiled and publically available, such as detail on habitats in which different species and life stages are caught, including effects of seasonality and water levels. The navigation industry could provide insights into the fundamental requirements to support navigation, which could facilitate discussion of alternative arrangements to support navigation.

The Water Institute could facilitate beneficial exchanges with industry in many ways. One would be to start informal conversations, beginning with industry scientists with whom Institute scientists already have some contacts. Invitations to present a seminar, followed by lunch or dinner, could represent easy, comfortable ways to initiate communication and interchange. Through such discussions on topics of common interests,

BOX 5-1
Future Energy Industry Coasts

As a "working coast" the lower Mississippi River and its delta bear comparison with other industrializing deltaic regions around the world, which may be pursued in part in collaboration with industry research partners and support. For example, the Gulf coast has witnessed an evolution of petrochemical industrial land use over the past century from the Spindletop oil strike in 1901 to shallow oil and gas production, refining, shipping, pipeline development, and associated waterfront petrochemical industries – to the development of ever deeper offshore drilling, pipeline extensions, and development of the Louisiana Offshore Oil Port since 1981. LSU's Energy Center and other Gulf industrial organizations have established oil spill research, containment, and remediation centers. The RESTORE Act and BP and related settlements will greatly increase this expertise.

As noted in Chapter 2, Louisiana has a working coast with a full suite of marine, deltaic, and riverfront petrochemical industries and related environmental sciences. Knowledge generated in the Mississippi River delta region will bear comparison with analogues of the Rhine and North Sea in oil exploration, shipping and marine research which were highlighted in Chapter 2. Here the emphasis is on potential research and collaboration that has relevance for other industrializing deltas, including the following:

- Niger delta – issues include oil spills, fisheries impacts, epidemiology, poverty, social conflict, human rights, security, and increasing scientific assessment related to corporate social responsibility (CSR).
- Shatt al Arab, Iraq – issues include sediment and flow reduction, pollution control, marsh destruction and restoration, and postconflict reconstruction in an arid environment (France, 2006; USACE; U.S. House of Representatives, 2004).
- Nile delta – issues include sediment and flow reduction, pollution control, marsh destruction and restoration, in an arid environment (USGS, 2012).
- MacKenzie River delta – Canadian arctic delta/North Slope Beaufort Sea
- Siberian arctic – growing exploration and development in Lena delta/Laptev Sea
- East and southeast Asian deltas – (Sidi et al., 2003).

Three foci seem particularly relevant for integrated water and environmental management in deltaic regions comparable to the Mississippi River delta: (1) natural gas exploration and pipeline channel restoration; (2) riparian and groundwater remediation, preparedness, and risk management associated with riparian petrochemical manufacturing complexes; and (3) environmental restoration associated with offshore development and spills. In the current context, knowledge gained from delta restoration, preparedness, and protection projects in the Mississippi River delta may have relevance for other coastal petrochemical regions. Various industry partnership and sponsorship models have been developed in university energy centers, and these approaches may have promise in the Mississippi and other regions.

with a small group of invited faculty, researchers, and graduate students, ultimately could lead to more extensive outreach.

A Gradient of Outreach Activities

The Water Institute's potential outreach activities could be viewed along a gradient from low-key and low-cost, to more ambitious outreach. As noted above, initial efforts should include invitations to individual scientists to present seminars and share meals, and in addition the Institute could initiate an interdisciplinary forum for free and open exchange of ideas, which could meet weekly, biweekly, or monthly. The forum can potentially be constituted as an interdisciplinary seminar co-taught with university faculty colleagues, alternating meetings between campus and the Water Institute. Depending on topics discussed, agency and industry scientists in the region could be invited to participate, and in some cases, relevant experts from afar could be invited to join.

In addition to this local/regional outreach, the Water Institute could facilitate national and international collaborations. A visiting scholar program could host scholars and managers from other institutions for weeks, months, or longer. A small number of visiting experts could be hosted with office space, Internet access, a stipend, and access to field equipment. The Water Institute could provide fellowships for faculty on sabbatical, fund postdoctoral scholars (or co-fund with universities), and also host managers and agency officials who have the opportunity to take sabbatical-type leaves, such as bureaucrats in the European Commission. The Water Institute also could work with the Fulbright Commission to host visitors. A disadvantage of the Fulbright-type programs is their long lead time, but advantages include the sharing of costs and the credibility of collaborating with Fulbright and others.

Convening biannual or triannual conferences on research on deltas worldwide could help establish the Water Institute as a global center of such research activity. These conferences could result in publications, or symposia summaries, that would become important reference works in the field. The Water Institute could also consider launching an *International Journal of Delta Research*, as a mechanism to further cement its role as a global center of delta research.

These activities, along with hosting PhD students, postdoctoral scholars, and senior scholars (not only faculty on sabbatical but also non-PhDs drawn from the ranks of managers and agency scientists), could serve to keep Water Institute scientists aware of research and management experience from deltas worldwide.

Equipment Library

By providing logistical support to researchers, the Water Institute could extend the spatial, temporal, or variable scope of experiments. One idea would be to organize an equipment library for fieldwork, usable by principal investigators (PIs) at reasonable fees (for external projects) or gratis on projects sponsored by the Water Institute. One barrier to conducting scientific research is that field equipment is expensive to purchase and maintain, and much of it sits on the shelf when not in use by the PI who owns it. An equipment library would shift the costs of the equipment infrastructure from PIs to the Water Institute, but the net cost of research should decrease because the equipment will have higher usage rates. The equipment library could arrange for equipment insurance to cover its equipment and allow PIs to share equipment under the umbrella of the Water Institute. This would eliminate insurance payments as a barrier to the lending of equipment and would support its fuller use.

INSTITUTE STRUCTURE AND ORGANIZATIONAL OPTIONS

As a new research entity without institutional constraints, the Water Institute has an unusual opportunity to develop a research scope and agenda, an organizational structure, and a mode of operation that are not encumbered by historical constraints. Even so, Water Institute leadership will recognize that their research will be conducted in a setting that is occupied by other entities that conduct research, implement regulations, or affect the environment through commercial or industrial practices. The Water Institute thus would benefit from a plan for interaction with universities, government agencies, or other organized entities that conduct or support research, and with industries that are economically important in the Gulf

The structural features of the Water Institute will also affect its long-term value and success. As it is not part of a university or government agency, the Water Institute will require a distinctive type of organizational structure. It constitutes a new model for a center of environmental research excellence. Thus, a specific staffing plan that builds competencies supportive of its intended purpose could help the Water Institute avoid overcommitting resources in some areas, addressed by other research organizations, and a deficiency of resources areas central to its purpose and structure.

Structure, Organizational Options, and Composition of the Institute

The Water Institute could employ a strategy that is adapted to its intended operations and goals as well as factors that constrain its work. Strategic factors to be considered by the Water Institute leadership include mode of operation, incentives and expectations for staff, mechanisms for prioritization of work, optimization of competencies, and efficient organizational structure.

Mode of Operation

At one end of the spectrum, the Water Institute could attempt to conduct all of its research and related activities on an independent basis, or conversely, it could serve mainly as a broker of research. More feasible and effective than either of these contrasting strategies, however, is a rational opportunistic mode of operation that favors independent work when the full range of competencies is available internally but moves to varying degrees of collaboration or even complete distribution of some types of work when such a mode of operation can result in a better product. Furthermore, partnerships will enhance the image of the Water Institute as part of an extended research community rather than an entity that finds limited benefits in sponsored collaboration.

Prioritization of Work

Research units that depend on contracts and grants, as will the Water Institute, have to balance pragmatism in developing a research agenda, while encouraging vision and bold thinking among its staff. Prioritization will involve not only an interest in funding but also a commitment to projects that are both feasible and significant.

Institute Structure

A clear and comprehensive organizational structure will facilitate internal communication, lines of authority, and interface with outside interests of the Water Institute. The Water Institute's organization might include not only an external advisory committee, as already exists, but also an internal science leadership group that holds a recognized responsibility for advising the director.

Core Competencies

Core competencies of research staff will reflect the research agenda. A hypothetical list of competencies is shown in Table 5-1, which is based on the assumption that the Water Institute will show competencies that reflect its commitment to a systems-level analysis of the delta environment. The commitment to systems analysis requires research competency in the disciplines environmental physics (geomorphology, hydrology), ecology

TABLE 5-1 Hypothetical Areas of Competency for Water Institute Staff

Competence	Comments
Geomorphology	Coastal zone geomorphic processes, soil development
Hydrology	Basic hydrology, engineering hydrology
Marsh Ecology	Habitat, food web dynamics
Fisheries	Environmental requirements, sustained yield
Geography	Digital mapping, remote sensing, land and water use
Modeling	Process models, systems models
Economics	Benefits-costs, policy alternatives and choices
History	Land and water development patterns; cultural heritage
Other social sciences	Decision making, institutions, human-environment relations, science-policy analysis, environmental and hazards perception

(marshes, fisheries), comprehensive measurement and assessment capabilities (geography), ability to quantify processes and make predictions (modeling), and ability to deal descriptively and quantitatively with human behavior, valuation, and institutions (social science). However, beyond these disciplinary fields of expertise, this report has stressed the role and importance of cultivating expertise in integrative research fields of environment-society interactions and hazards research.

If it proves infeasible or undesirable for the Water Institute to form a core structure that has a range of competencies reflective of the list shown in Table 5-1, the Water Institute may wish to commit itself to near- or long-term partnerships with research entities that offer these competencies. Alternatively, the Water Institute could choose to specialize in specific aspects of environmental analysis in the delta. If the Water Institute is to take a unique role as a leader in systems-level analysis of delta environments, with emphasis on the Gulf delta region of the Mississippi River, a systems-level array of competencies is essential for credibility.

The competencies shown in Table 5-1 not only address the capability of the Water Institute in dealing at the systems level with the Gulf environment, but also reflect the agents of change discussed in Chapter 2. For example, expertise in geomorphology establishes the Water Institute's capability for dealing with dynamics of land surface area in the Gulf, with sediment mass balance and distribution, and with geomorphic processes that enhance the potential for development of marsh landscapes. Inclusion of social science expertise in the list of competencies would encourage analytical expertise for describing and projecting the effects of delta populations and institutions within the delta environment, and could contribute to an integrated perspective for water and environmental management within the Water Institute.

- **The Water Institute will have opportunities to build working, collaborative relationships with a rich variety of research and educational institutes, and private industry—including energy exploration and development firms, fisheries, tourism, and the maritime transportation sector.**

  Examples of these opportunities include hosting international seminars, scholar exchange, establishment of a special delta research journal, and insurance for laboratory facilities or research equipment.

6

Comparative International Deltaic Research: Transferring and Applying Knowledge

This chapter on comparative international research opportunities addresses the topic of "Transferring and Applying Knowledge" in the Statement of Task. On the one hand, the Mississippi River delta is unique, given its combination of bird's-foot morphology, low tidal range, high storm vulnerability, spatially concentrated but important urbanization, and large-scale industrial development and commercial fisheries. Just as geographer Gilbert F. White (1957) noted that "No two rivers are the same," as he was embarking on a comparative study of international river basins, so too may it be said that no two deltas are the same. On the other hand, the Mississippi River delta does have attributes, expertise, and approaches that can be compared with other deltas, and that can shed light on environment-society relations in ways that help broaden the range of choice among water management alternatives in those regions.

Comparative water resources and deltaic research is at an exciting, yet challenging, stage of development. Growing concern about deltas, coupled with new tools for data-driven analysis, and new scientific networks are stimulating comparative international inquiry (e.g., Brakenridge et al., 2013; Bucks, et al. 2010; Coleman et al., 2008; Ericson, Vörösmarty et al., 2006; Overeem and Syvitski, 2009; Paola et al., 2011; Syvitski et al., 2009; Vermaat and Elevald, 2013). Emerging international delta networks include Connecting Delta Cities, Delta Alliance, Louisiana Universities Gulf Research Collaborative, National Center for Earth Surface Dynamics, USGS DRAGON, the German-Vietnamese WISDOM initiative, the World Estuary Alliance, and others.

Even so, the historical record cautions against an overly broad approach to international comparison. A significant review of international delta studies was given by Roberts and Coleman (2003) in their 50-year history of the LSU Coastal Studies Institute. That account explained how the early impetus and continuing funding for international coastal research came from the Office of Naval Research (ONR), which was initially driven by geomorphological challenges to beach landings during World War II. Scientists funded by ONR went on to advance the basic science of deltaic geomorphology. When ONR restructured its research funding, the Coastal Studies Institute had to adjust its research program. Other research and engineering organizations have had changing programs of lower river and deltaic research that deserve rigorous historical review; they include Delft Hydraulics, the French Ecole des Ponts et Chaussees, and U.S. Army Corps of Engineers (Shallat, 1994).

In smaller organizations, a group of committed scientists can create a broad international program, but may not be able to sustain that research agenda over the long-term of multiple decades and generations. The Water Institute has limited staffing, even with significant anticipated growth and its expanding mission in the Mississippi River delta. By comparison, Deltares has over 800 employees and a program of international research that has developed over nearly a century from its origins as Delft Hydraulics. Pursuing international opportunities within the context of practical constraints can be achieved in part through a strategic approach for screening research projects.

A FRAMEWORK FOR COMPARATIVE INTERNATIONAL RESEARCH

The comparative water research field contains many examples of disparate short-term studies and conference proceedings assembled with little rigorous analysis across cases or variables (Wescoat, 2009). To move beyond this pattern, the Water Institute would benefit from a conceptual framework and criteria for screening comparative deltaic research projects. For example, opportunities for comparative international inquiry can be organized by their *aims* (purposes) and *levels* (scope and methods). This approach is illustrated below.

Aims of Comparative International Inquiry:

1. *Problem-driven research (learning)*—Pursue strategic research that is already under way in the Gulf and that may be studied in another delta.
2. *Opportunity-driven research (transferring knowledge)*—Transfer ex-

pertise developed through delta restoration research in the Gulf to other deltaic regions

3. *Perspective-driven research (teaching and learning)*—Develop an interpretive perspective on work under way in the Mississippi gulf through partial analogues and contrasts with innovations and practices in other deltas.
4. *Network-driven research*—Develop a regular program of engaging international delta research and management leaders at the Institute.
5. *Human and social capital-driven research*—Disseminate and raise the profile of the Water Institute's work and staff in international forums and major collaborative studies.

Levels of Comparative International Inquiry:

There are several major levels and associated methods of comparative inquiry, which may be distinguished for conceptual purposes (Mollinga and Gondelekhar, 2012; Wescoat, 2009):

1. *Quantitative comparison of global delta databases(large-N)* – Studies of 15 to 100 cases seek generalizations across a large number of cases controlling for different variables (e.g., wetland loss rates, subsidence rates, sea level rise, storm frequency and surge height, vulnerable populations and assets).
2. *Mixed quantitative and qualitative comparison of thematic issues (intermediate-N)* – Studies of 5 to 15 cases are useful for grouping deltas and conducting thematic studies of vulnerability, resilience, and sustainability. Their mixed-methods can produce well-structured multidisciplinary studies (e.g., Renaud and Kuenzer, 2012). More formal qualitative methods have been developed, but they are not often employed in comparative water resources research (e.g., Boolean algebraic methods described by Ragin, 1987).
3. *Detailed qualitative comparison of individual deltas (small-N)* – Studies of one to five deltas are among the most detailed and challenging types of comparative water research. They include place-specific historical studies of deltaic development and knowledge transfer. Construction of analogies between paired cases is also used in research on the human dimensions of climate change and adaptation (Glantz, 1988; Meyer et al., 1998).

These two dimensions of comparative research can be viewed in a matrix format to clarify international research priorities (Figure 6-1). All levels of international comparison can shed light on problems in the lower Mississippi River delta, and can help build human and social capital. They do so

Levels/aims	Problems	Opportunities	Perspectives	Networks	Human/social capital
Large-N	x		x		x
Medium-N	x			x	x
Small-N	x	x			x

FIGURE 6-1 Comparative research matrix for clarifying international research priorities.
NOTE: This matrix displays relationships between aims and types of comparative inquiry. X's indicate associations that may have a higher level of potential significance for the Water Institute's comparative research agenda.

in different ways: to generalize, global quantitative research can help situate the Mississippi in a wider context; while multimethod thematic studies can address science-policy questions; and paired delta studies are the principal vehicle for transferring and applying lessons.

- **The Water Institute could define traits that best characterize the Mississippi Delta, and begin to establish connections and comparisons with a small, diverse set of other delta regions. The Water Institute subsequently could branch out as interests and staff resources permit.**
- **To help prioritize its own international activities and its collaborations with other delta regions, the Water Institute could develop and employ a simple framework of international research *aims* and *methods* to screen, rank, and select its international activities.**

EXAMPLES OF COMPARATIVE DELTAIC RESEARCH

Global Delta Comparisons Based on a Large Number of Cases

Several major scientific research programs have included scores of delta cases. The first international delta databases were prepared in the 1970s by the LSU Coastal Studies Institute (Coleman and Wright, 1973, 1975; Wright et al., 1974). This work evolved into the World Delta Database based at LSU (Coleman and Huh, 2004; Huh et al., 2004). Analysis of new delta datasets has been undertaken with MODIS remote sensing studies of lower floodplains and deltas—for example, at the University of Colorado-Boulder (Syvitski et al., 2009); the LOICZ study of deltaic processes in the IGBP Land-Ocean Interface studies (Overreen and Syvitski, 2009); and Vermaat and Eleveld's (2013) principal components analysis of the DIVA coastal segment database, which includes variables on populations at risk as well as coastal physical conditions and global change scenarios. Datasets of this size situate the lower Mississippi River delta quantitatively within global rates of deltaic land loss, inundation, turbidity, change in land use and land cover, and populations at risk.

Thematic Delta Comparisons Based on an Intermediate Number of Cases

The intermediate level of comparison usually involves around 5 to 15 cases. An early cluster analysis of 34 deltas—based solely on physical attributes of drainage basins, deltaic plains, and receiving basins—identified seven clusters of deltas (Coleman and Wright, 1977). The seven clusters were not strongly associated, but they did display interesting patterns of physical similarity and dissimilarity, in which the Mississippi River delta was found to be physically similar to the Colville and Danube deltas (Figure 6-2). Multivariate analysis with the new international databases may group deltas by environmental and socioeconomic agents of change, which would be useful for integrated water and environmental management (e.g., Vermaat and Eelvald, 2013).

Comparison for management purposes often entails a mix of quantitative and qualitative methods. An example is the recent Delta Alliance *Comparative Assessment of the Vulnerability and Resilience of 10 Deltas*, which convened study teams in each of the 10 deltas. This study developed a scorecard for the four "layers" of delta management—the natural base layer, the infrastructure layer, the socioeconomic occupance layer, and the governance layer. It identified four to six major types of research needs and gaps for each layer (Table 6-1). The researchers assessed each delta's vulnerability and resilience under three scenarios of climate change (see Table 2-3).

That study of 10 deltas reported the Mississippi River delta's main research gaps as: socioeconomic scenarios; effects of development on ecosystem functions, building with nature (i.e., ecological design), data management, and research on governmental roles and policies. Based on this appraisal, vulnerability of the Mississippi River delta ranked moderately among the 10 deltas. It ranked below the Rhine and Danube, on a par with the California Bay-Delta and Mekong, and as somewhat less vulnerable than other large deltas in Asia. This study offers one way of thinking about

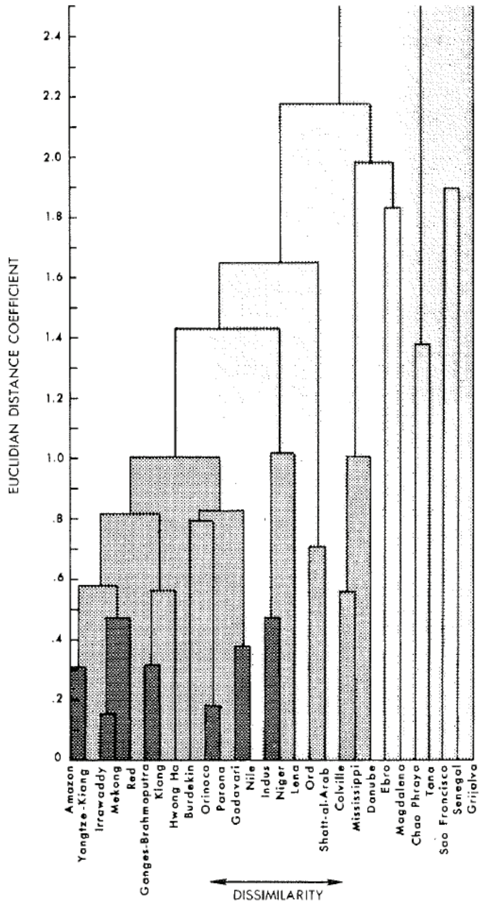

FIGURE 6-2 Cluster analysis of physical delta attributes.
SOURCE: Coleman and Wright, 1977.

comparisons relevant for integrated water and environmental management in the Mississippi River delta and transferring lessons to other regions.

Detailed Delta Comparisons Based on a Small Number of Cases

The most frequent, and often most difficult, type of comparison involves two detailed case studies. Detailed information underscores the differences in both physical and social systems, which works against quantitative comparison and direct application from one region to another. For

TABLE 6-1 Research Needs and gaps for the Four Layers of Delta Management

	Nile	Incomati	Ganges-Brahmaputra-Meghna	Yangtze	Ciliwung	Mekong	Rhine-Meuse	Danube	California Bay-delta	Mississippi River delta
Occupation layer										
Socio-economic scenarios (6)	●	●		●	●			●		●
Water use and treatment (5)	●	●	●		●		●			
Integrated spatial planning (5)	●	●	●		●		●			
Ecosystem services (5)	●			●	●		●	●		
Land-use change modelling (4)	●		●		●				●	
Adaptation to salinisation (2)	●		●							
Network layer										
Freshwater management (7)	●	●	●		●	●	●		●	
Dikes and dams (5)	●		●		●		●		●	
Transport (3)	●	●			●					
Flood forecasting/early warning systems (1)			●							
Base layer										
Effects of changes/ eco-system functioning (9)	●	●	●	●	●		●	●	●	●
Building with nature and natural safety (8)	●		●	●	●	●	●	●		●
Monitoring changes (7)	●		●	●	●	●	●		●	
Predicting changes (7)	●		●		●	●	●	●	●	
Base-layer data management (3)			●		●					●
Governance										
Governmental roles and arrangements (6)	●				●	●	●		●	●
Integrated delta management (6)	●	●	●	●	●			●		
Communication/capacity building (4)	●	●	●		●					
Financial arrangements (4)			●		●		●		●	
River basin cooperation (2)		●	●							
Policy impact studies (1)					●					

Comparative assessment of the vulnerability and resilience of 10 deltas | synthesis report

SOURCE: Bucks et al., 2010.

this reason, detailed case studies often involve the construction of analogies between cases, which is a type of research used in climate change adaptation research (e.g., Glantz, 1988). Analogies are based on a qualitative similarity or difference in one variable that suggests similarities or differences in other variables (Meyer et al., 1998). Analogies can be used to generate scenarios of possible future conditions that can help expand the range of environmental conditions, alternatives, and innovations to be considered. For that reason, analogues and analogies are sometimes said to be more or less useful, rather than more or less valid. Several examples follow that involve one, two, and three cases.

Single Delta Comparisons

A delta can be compared with itself. Examples include comparisons of the Mississippi River delta with itself over time (e.g., comparative statics before and after the Coastal Zone Management Act, Hurricane Katrina, or the Deepwater Horizon spill). More specifically, it would be interesting to compare coastal zone management research in Louisiana in the mid-1970s when diversions for restoration were proposed but not accepted, with the 2012 Coastal Master Plan when diversion plans were unanimously adopted. What new knowledge and new uses of knowledge explain this change? How might future knowledge operate at time scales of years rather than decades?

Paired Comparisons

Rhine-Mississippi comparisons have been discussed throughout this report. They include the Dutch Dialogues and other exchanges on flood hazards planning, "Room for the River," and urban environmental design competitions (Delta Alliance, 2010; Meyer et al., 2009; NUWCRen, 2012; Wesselink, 2007). Some of the more conceptually challenging analogies with the Rhine include governance structures, spatial planning, and large-scale coastal engineering. Use of these analogies could suggest integrated water and environmental management approaches for the Mississippi

Ganges-Brahmaputra-Mississippi comparisons have historically operated in the other direction, with lessons drawn from the Mississippi to Bengal delta from the time of economist Radhakamal Mukerjee (1938) to the early work of the LSU Coastal Studies Institute, and critical studies of the Bangladesh Flood Action Plan in the 1990s (e.g., Brammer, 2010; Rogers et al., 1989). Louisiana potentially could exchange ideas with Bangladesh on large-scale cyclone shelter performance and evacuation, public health and oral rehydration therapy in disaster relief, and mechanisms of microfinance in hazards mitigation and recovery. Such analogies stimulate the imagination to encompass new lines of integrated water research that may be of practical use in the Mississippi River delta and beyond.

Mekong-Mississippi comparisons have occurred from the river basin to deltaic scales (Jacobs, 1999). USGS's National Wetlands Center in Lafayette, Louisiana, has a major Forecast Mekong study program under way (Turnipseed, 2013). Documentation for the program is an impressive example of knowledge transfer, supported in part by the U.S. State Department initiative (see Box 6-1). It is an open question as to how managers in the Mississippi River delta could benefit from knowledge generated in the Mekong. The conceptual framework offered above suggests that the Forecast Mekong example fulfills the "opportunities," "perspectives," "network," and "human capital" aims of comparative research.

BOX 6-1
The Mekong River and Delta

The Lower Mekong River and delta provide a potential precedent for US-based expertise being applied internationally, which could serve as a model for the Water Institute's future international efforts (though see Biggs, 2011 for a critical history of such efforts). The Mekong River (drainage area 800,000 km^2 average discharge 15,000 m^3s^{-1}) is unique among the world's great rivers in the size of the human population supported by its ecosystem. Approximately 60 million people (mostly in Cambodia and Vietnam) derive their livelihoods from aquatic life in the river system (Campbell, 2009). Since the early 1990s, the basin has experienced rapid development, including over 140 dams proposed, under construction, or built. How these dams will affect the river and its ecosystem are key questions facing the region, but basic data such as detailed bathymetry and fish life histories are very limited.

Since 2009, the U.S. Geological Survey's Wetlands Research Center in Lafayette has coordinated Forecast Mekong, a project under the Delta Research and Global Observation Network (DRAGON), in cooperation with in-basin partners in Cambodia, Laos, Vietnam, and Thailand (http://deltas.usgs.gov/fm/). One of the first products is a graphic visualization program of bathymetry and hydrology for the confluence of the Tonle Sap and Mekong rivers, near Phnom Penh. The program development process provided the opportunity for hands-on training on multibeam sonar and acoustic Doppler current profiler instrumentation, thereby transferring technology and skill to the region, ultimately for construction of a complete bathymetric map of the lower Mekong River and key tributaries. Another effort is the Mekong Fish Monitoring Network to address the need for data on fisheries. A 2012 pilot fish monitoring study was designed to build capacity within basin states and provide a platform for data sharing and analysis. Other initiatives under Forecast Mekong are citizen science for salinity monitoring in the delta, and making available scanned historical maps and satellite imagery to government agencies and members of the public.

Another ongoing effort is the USAID-funded Climate-Resilient Mekong initiative of the Natural Heritage Institute, working with water ministry staff of Cambodia, Laos, Thailand, Vietnam, and China to explore alternative dam designs that would reduce environmental impacts (notably by trapping less sediment and allowing migration of fish) while having comparable electric generation capabilities. This project has involved the first geomorphically based analysis of probable sediment-starvation impacts of dams as currently proposed, reservoir operation and sediment transport modeling for selected tributaries and mainstem sites, and development of alternative dam designs in workshops with staff of the lower basin states. Other international research groups are actively engaged in the Mekong, making it a focus of international scientific inquiry on sediment, sea level, fishing, and agriculture (Renaud and Kuenzer, 2012).

BOX 6-2
A Regional Example: Major Deltas in China

China has three major delta ecosystems associated with the Yellow (Huanghe), Yangtze (Changjiang), and Pearl (Zhujiang) rivers. The Huanghe Delta is characterized by high sediment loading and discharge, thin Holocene deltaic sediments, a lateral delta lobe shift, and a steep longitudinal profile in its lower reaches. The Changjiang delta is characterized by a large water discharge with dramatic seasonality, a tide-dominated coastal environment, thick Holocene sediments, and a deep-incised valley that formed during the last glacial period (Saito et al., 2001). The Zhujiang is a composite delta that is impacted by large flow discharge, low-lying areas, and a dense network of tributaries.

Although the three deltas are unique in their geomorphological and socioeconomic conditions, they face some common problems, including (1) Heavily regulated flow and sediment discharges by reservoirs and dams and water withdrawals in the upstream areas. The flow to the Huanghe Delta was entirely cut off almost every year during the 1990s; the sediment discharge to the Changjiang delta shows a strong decreasing trend from the late 1960s to 2003, likely due to dam construction (Yang et al., 2005). (2) Vulnerability to flood: Flood risk is increasing in Changjiang delta because of the subsidence, coastal wetlands degradation and climate change; in Huanghe delta because of the sediment accumulation in the downstream river channel; and in the Zhujiang delta because of concentrated rainfall, typhoons, and low-lying areas and dike-building practices over one thousand years. (3) Water pollution. The Zhujiang delta is polluted by sewage discharge from a dense network of cities that lie along its path. The Changjiang delta has been threatened by upstream sewage discharge untreated and salt water intrusion due to sea level rise. (4) Declines in upstream runoff and inflow due to more frequent droughts and the possible impact(s) of climate changes, with future concerns of glacier retreats. (5) Intensive human interferences in the delta area and vulnerable ecosystems. The Changjiang and Zhujiang deltas are highly urbanized, supporting the wealthiest and most economically dynamic regions of China. Land and water use in those areas has already caused substantial ecosystem degradation. Although the Huanghe delta is much less developed (probably due to its unstable natural state), it is recognized as an area with a large potential of economic development in China, and rapid development has been seen in recent years. Consequently, the wetlands and biodiversity in all these deltas have been degrading.

The existing measures and plans to protect the major deltas in China are influenced by a basin-wide systems approach coordinated by the commission established for each of the major basins under the Ministry of Water Resources. For example, in order to avoid flow cut-offs occurring in the 1990s, the Yellow River Conservancy Commission implemented the “Water Allocation Program” approved by the State Council of China, which specifies water withdrawal quotas for provinces along the basin.

Three Delta Comparisons

Three-way comparisons can reduce the emphasis on differences in any single pair. An example is provided by a Deltares (2012) study of adaptive management in the Netherlands, United States, and East Asia. Another hypothetical example could involve a three-way international research project among the Mississippi, Rhine, and Ganges-Brahmaputra deltas. Scientists in each of these deltas have engaged in research on the others, sometimes with links to integrated water and environmental management. International debates about the Bangladesh Flood Action Plan in the 1990s and subsequent plans may not yet have been fully absorbed in integrated water management for deltaic regions. Another three-way comparison could involve water researchers in U.S. and Chinese deltas. Likewise, the Mississippi River and Chinese deltas have the possibility of creating a new level of scientific network and institution-building (see Box 6-2).

TIMESCALES FOR KNOWLEDGE TRANSFER

Analogues between the Mississippi and other deltas of the world were introduced in Chapter 2. This section discusses ideas about knowledge transfer from the Mississippi River delta to and for other regions. It begins with near-term international collaborative research and proceeds toward longer-term research strategies.

Near-Term International Water Research

The Water Institute is now involved in international delta networks, international research projects, and an expanding working relationship with Deltares in the Netherlands (Deltares, 2013). These collaborations will enhance the capacity of Water Institute scientists and lead to identification of more research approaches and methods that could be useful both in the Mississippi River delta region and for transfer to other deltas.

A conservative position on knowledge transfer to other regions may be appropriate for the Water Institute in its initial years. One lesson of late twentieth century international water resources research and development involved risks and failures caused by uncritical transfer of water management practices. Failures included modeling with inadequate data; infrastructure approaches that proved unsustainable; well-intentioned groundwater development that aggravated water quality hazards; and research contingent upon rapidly changing geopolitical and trade relations. In each case, investigators sought to do good but had mixed or adverse results.

- **In the near term, a small set of strategic gulf-centric studies may be the main type of international research on analogies that the Water Institute undertakes.**
- **Over the medium term, Water Institute scientists would benefit from strategic engagement in multidelta comparisons, such as the Delta Alliance's study of vulnerability and resilience.**

Longer-Term Knowledge Transfer Opportunities

As the Water Institute develops expertise in particular research applications, like delta restoration ecology, it may wish to expand its role in international transfer of knowledge. That might include identification of long-term "paired delta" alliances. Some promising examples include the Mississippi-Bengal deltas for applied research on hydrodynamics, sediment transport, coastal hazards, demography, health and epidemiology; Mississippi-Chinese deltas for applied research on sediment transport, deltaic urbanism, infrastructure, and environment; Mississippi-Mekong deltas for applied research on sediment, fisheries, and ecohydrology; and the Mississippi-Niger deltas and other petrochemical-based industrializing deltas for applied research on energy development, environmental management, and social equity.

In the near term, the Water Institute may have the most promise for collaborative research with international delta researchers and organizations that seek to exchange knowledge between the Mississippi River delta and other regions. Over the longer term, knowledge transfer to a small number of deltas in areas of the Water Institute's special expertise may be developed through specific mechanisms that advance from a "project" to a "programmatic" level.

- **In the longer term, depending upon its Mississippi River priorities and expertise, the Water Institute may be in a position to develop a small number of continuous, cooperative problem-driven and thematic research programs with other delta regions.**

  Examples include (1) environmental/ecosystem restoration—Rhine, Danube, Irrawaddy; (2) natural hazards mitigation—Ganges-Brahmaputra, and Mekong; (3) energy industry, environment, and conflict—Niger, Yellow River, Indian Ocean, Arctic deltas; (4) sediment trapping and land loss—Mekong and Yellow; and (5) urban planning and flood risk reduction—in New Orleans, the Connecting Delta Cities program, Pearl, and Yangtze deltas.

References

Allison, M. A., M. T. Ramirez, B. M. Vosburg, and E. A. Meselhe. 2013. Mississippi River channel response to the Bonnet Carré Spillway opening in the 2011 flood and its implications for the design and operation of river diversions. Journal of Hydrology 477:104-118. Available at http://dx.doi.org/10.1016/j.jhydrol.2012.11.011. Accessed August 12, 2013.

Angelaksi, A., L. Mays, D. Koutsoyiannis, and N. Mamassis. 2012. Evolution of Water Supply Through the Millennia. London: IWA Publishing.

Barry, J. M. 1997. Rising Tide: The Great Mississippi River Flood of 1927 and How It changed America. New York: Touchstone.

Beveridge, R., and J. Monsees. 2012. Bridging parallel discourses of Integrated Water Resources Management (IWRM): Institutional and political challenges in developing and developed countries. Water International 37(7):727-743.

Bianchi, T. S., and M. A. Allison. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences 106(20):8085-8092.

Biggs, D. 2011. Fixing the delta: History and the politics of hydraulic infrastructure development and conservation in the Mekong Delta. Pp. 35-44 in Environmental Change and Agricultural Sustainability in the Mekong Delta, M. A. Stewart and P. A. Coclanis, eds. Advances in Global Change Research, v. 45. Dordrecht: Springer.

Biswas, A. K. 2008. Integrated water resources management: Is it working? Water Resources Development 24(1):5-22.

Blum, M. D., and H. H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience 2:488-491.

Bosselmann, P. C., G. M. Kondolf, J. Feng, G. Bao, Z. Zhang, and M. Liu. 2010. The future of a Chinese water village: Alternative design practices aimed to provide new life for traditional water villages in the Pearl River Delta. Journal of Urban Design 15(2):243-267.

Brakenridge, G. R., J. P. M. Syvitski, I. Overeem, S. A. Higgins, A. J. Kettner, J. A. Stewart-Moore, and R. Westerhoff. 2013. Global mapping of storm surges and the assessment of coastal vulnerability. Natural Hazards 66:1295-1312.

Brammer, H. 2010. After the Bangladesh Flood Action Plan: Looking to the future. Environmental Hazards 9:118-130.

Bruggeman, W., S. Hommes, M. Haasnoot, A. Te Linde, and R. van der Brugge. 2011. Deltascenario's: Scenario's voor robuustheidanalyse van maatregelen voor zoetwatervoorziening en waterveiligheid—in Dutch (Deltascenarios: Scenarios for Robustness Analysis of Strategies for Fresh Water Supply and Water Safety). Delft, Netherlands: Deltares.

Bucks, T., M. Marchand, A. Makaske, and C. van de Guchte. 2010. Comparative Assessment of the Vulnerability and Resilience of 10 Deltas—Synthesis Report. Delft-Wageningen, Netherlands: Delta Alliance International.

Campanella, R. 2002. Time and Place in New Orleans: Past Geographies in the Present Day. Gretna, LA: Pelican Publishing.

Campanella, R. 2010. Delta Urbanism: New Orleans. Washington, DC: APA Planners Press.

Campbell, I. C. 2009. The Mekong: Biophysical Environment of an International River Basin. Waltham, MA: Academic Press.

Cardwell, H. E., R. A. Cole, L. A. Cartwright, and L. A. Martin. 2006. Integrated water resources management: Definitions and conceptual musings. University Council on Water Resources. Journal of Contemporary Water Research and Education 135:8-18.

Chenoweth, J. 2012. Key issues and trends in the water policy literature. Water Policy 14:1047-1059.

CPRA (Louisiana Coastal Protection and Restoration Authority). 2010. Map of projected subsidence ranges for south Louisiana. Online. Available at http://www.mississippiriverdelta.org/blog/2012/02/29/new-report-outlines-recommendations-for-anticipating-sea-level-rise-impacts-on-louisiana%E2%80%99s-coast/. Accessed July 3, 2013.

CPRA. 2012. Louisiana's Comprehensive Master Plan for a Sustainable Coast. Baton Rouge: CPRA.

Coleman, J., and O. K. Huh. 2004. Major World Deltas: A Perspective from Space. World Delta Database. Online. Available at http://www.geol.lsu.edu/WDD/PUBLICATIONS/introduction.htm. Accessed July 5, 2013.

Coleman, J., O. K. Huh, and D. Brand, Jr. 2008. Wetland loss in world deltas. Journal of Coastal Research 24(1A):1-14.

Coleman, J. M., and L. D. Wright. 1973. Variability of modern river deltas. Transactions, Gulf Coast Association of Geological Societies 23:33-36.

Coleman, J. M., and L. D. Wright. 1975. Modern river deltas: Variability of processes and sand bodies. Pp. 99-149 in Deltas: Models for Exploration, M. L. Broussard, ed. Houston, TX: Geological Society.

Coleman, J. M., and L. D. Wright. 1977. Research techniques in deltas. Proceedings, Symposium on Research Techniques in Coastal Environments (Russell Symposium), Geoscience and Man Series, School of Geoscience, Louisiana State University 18:35-51.

Collier, C. R. 2004. Sustainable water resources management in the United States: Use of river basin commissions to promote economic development, while protecting the environment and improving community quality. Pp. 47-62 in Promoting Sustainable River Basin: Governance: Crafting Japan-U. Chiba, Japan: Institute of Developing Economies Japan External Trade Organization (IDE-JETRO).

Colorado Water Institute. 2010. Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management. Colorado Water Institute Information Series, no. 109. Online. Available at http://www.cwi.colostate.edu/publications/is/109.pdf. Accessed July 29, 2013.

Colten, C. E., R. W. Kates, and S. B. Laska. 2008. Community Resilience: Lessons from New Orleans and Hurricane Katrina. Online. Available at http://www.resilientus.org/library/FINAL_COLTEN_9-25-08_1223482263.pdf. Accessed March 6, 2012.

Dartmouth Flood Observatory. 2010. Geographic Centers of Floods, 1985-2010. Online. Available at http://floodobservatory.colorado.edu/Archives/index.html. Accessed July 3, 2013.

Day, J. W., Jr., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, K. Orth, H. Mashriqui, D. R. Reed, L. Shabman, C. A. Simenstad, B. J. Streever, R. R. Twilley, C. C. Watson, J. T. Wells, and D .F. Whigham. 2007. Restoration of the Mississippi delta: Lessons from hurricanes Katrina and Rita. Science 315:1679-1684.

Day, J. W., W. M. Kemp, A. Yanez-Arancibia, and B. C. Crump. 2012. Estuarine Ecology. 2nd ed. New York: Wiley-Blackwell.

Delta Alliance. 2010. Innovative Solutions for the Delta, Innovative Ideas for Delta Cities to Respond to Climate Change Challenges in the Complex Urban Environment. Wageningen, The Netherlands: Delta Alliance.

Deltacommissie. 2008. Working Together with Water: A Living Land Builds for Its Future. Findings of the Deltacommissie. The Hague: Deltacommissie.

Deltares. 2009. Onze Delta, Onze Toekomst, Staat en Toekomst van de Delta 2009. Delft, The Netherlands: Deltares.

Deltares. 2011a. Towards a Mekong Delta Plan, Synthesis of Water Sector Assessment. Delft, The Netherlands: Deltares.

Deltares. 2011b. An annotated bibliography on "research by design." Delft, The Netherlands: Deltares.

Deltares. 2012. Adaptive Water Management for Delta Regions: Towards GREEN Water Defense in East Asia. Delft, The Netherlands: Deltares.

Deltares. 2013. Water Institute, Deltares USA Form Research Partnership. Online. Available at http://www.deltares.nl/en/news/news-item/item/15696/water-institute-deltares-usa-form-research-partnership. Accessed August 12, 2013.

Dokka, R. K., G. F. Sella, and T. H. Dixon. 2006. Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America. Geophysical Research Letters 33. L23308. Online. Available at doi:10.1029/2006GL027250. Accessed August 12, 2013.

Eisenstein, W., G. M. Kondolf, and J. R. Cain. 2007. ReEnvisioning the Delta: Alternative Futures for the Heart of California. Berkeley: Institute for Urban and Regional Development, University of California, Berkeley.

EPA (U.S. Environmental Protection Agency). 2006. Ecoregions of Louisiana. Online. Available at ftp://ftp.epa.gov/wed/ecoregions/la/la_map.pdf. Accessed July 3, 2013.

Ericson, J. P., C. J. Vörösmarty, S. L. Dingman, L. G. Ward, and M. Meybeck. 2006. Effective sea-level rise and deltas: Causes of change and human dimension implications. Global Planetary Change 50:63-82.

Foufoula-Georgiou, E., et al. 2011. International Year of Deltas 2013: A proposal. Eos, Transactions American Geophysical Union 92(40):340-341.

Gagliano, S. M. 2002. Fault-Related Subsidence and Land Submergence in Southeastern Louisiana. New Orleans, LA: New Orleans Geological Society.

Gagliano, S. M. 2005. Effects of earthquakes, fault movements, and subsidence on the south Louisiana landscape. The Louisiana Civil Engineer, Journal of the Louisiana Section of the American Society of Civil Engineers 13(2):5-22.

Galloway, G. E. 2011. A plea for a national coordinated water policy. The Bridge, National Academy of Engineering 41(4):37-46.

Galloway, G. E., D. Boesch, and R. R. Twilley. 2009. Restoring and protecting coastal Louisiana. Issues in Science and Technology 25(2):25-38.

Giosan, L., and J. P. Bhattacharya. 2005. New directions in deltaic studies. River deltas: Concepts, models, and examples. SEPM Special Publications 83:3-10.

Glantz, M. H. 1988. Societal Responses to Regional Climatic Change: Forecasting by Analogy. Boulder, CO: Westview Press.

Glantz, M. H., ed. 1999. Creeping Environmental Problems and Sustainable Development in the Aral Sea Basin. New York: Cambridge University Press.

GWP (Global Water Partnership). 2000. Integrated Water Resources Management. Stockholm: GWP.

GWP. Rogers, P., and A. W. Hall. 2003. Effective Water Governance: Learning from the Dialogues. Stockholm: GWP.

GWP. Rees, J. A., J. Winpenny, and A. W. Hall. 2008. Water Financing and Governance. Stockholm: GWP.

Goolsby, D. A., and W. A. Battaglin. 2001. Long-term changes in concentrations and flux of nitrogen in the Mississippi River basin, USA. Hydrological Processes 15(7):1209-1226.

Groves, D. G., J. R. Fischbach, D. Knopman, C. Sharon, D. R. Johnson, D. S. Ortiz, P. B. Bryant, M. Hoover, and J. Ostwald. 2013. Addressing Coastal Vulnerabilities Through Comprehensive Planning. Santa Monica, CA: The RAND Corporation.

Haasnoot, M., J. H. Kwakkel, W. E. Walker, and J. Maat. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 23(2):485-498.

Hodges, B. R., J. E. Furnans, and P. S. Kulis. 2011. Case study: a thin-layer gravity current with implications for desalination brine disposal. Journal of Hydraulic Engineering-ASCE, 137:356-371.

Huh, O. K., J. M. Coleman, D. Braud, and L. Kiage. 2004. The Major River Deltas of the World. Baton Rouge: Louisiana State University Coastal Studies Institute.

Humborg, C., V. Ittekkot, A. Cociasu, and B. von Bodungen. 1997. Effect of Danube River dam on Black Sea biogeochemistry and ecosystem structure. Nature 386:385-388.

Ingram, H., D. E. Mann, G. D. Weatherford, and H. J. Cortner. 1984. Guidelines for improved institutional analysis in water resources planning. Water Resources Research 20(3):323-334.

IPET (Interagency Performance Evaluation Task Force). 2008. Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System: Final Report of the Interagency Performance Evaluation Task Force. U.S. Army Corps of Engineers.

Islam, S., and Susskind, L. 2012. Water Diplomacy: A Negotiated Approach to Managing Complex Water Networks. Washington, DC: Resources for the Future Press.

Jacobs, J. W. 1999. Comparing river basin development experiences between the Mekong and the Mississippi. Water International 24(3):196-203.

Jonkman, S. N., M. Bočkarjova, M. Kok, and P. Bernardini. 2008. Integrated hydrodynamic and economic modeling of flood damage in the Netherlands. Ecological Economics 66:72-90.

Kearney, M. S., J. C. A. Riter, and R. E. Turner. 2011. Freshwater river diversions for marsh restoration in Louisiana: Twenty-six years of changing vegetative cover and marsh area. Geophysical Research Letters 38, LI 6405. Online. Available at doi:10.1029/2011GL047847. Accessed August 12, 2013.

Kelley, R. 1989. Battling the inland sea: American political culture, public policy, and the Sacramento Valley, 1850-1896. Berkeley: University of California Press.

Kondolf, G. M., and H. Piégay. 2010. Geomorphology and society. Chapter 6 in Handbook of Geomorphology, K. Gregory, ed. London, England: SAGE Publications.

Kondolf, G. M., and K. Podolak. 2013. Space and time scales in human-landscape systems. Environmental Management (in press). DOI 10.1007/s00267-013-0078-9.

Kroon, T., and E. Ruijgh. 2012. Deltamodel, Functionele specificaties, kwaliteitseisen en opbouw Deltamodel—in Dutch (Delta Model, Functional Specifications, Quality Control and Setup of the Delta Model). Utrecht, The Netherlands: Ministerie van Infrastructuur en Milieu-Rijkswaterstaat.

Lee, K. 1999. Appraising adaptive management. Conservation Ecology 3(2):3. Online. Available at http://www.ecologyandsociety.org/vol3/iss2/art3/. Accessed June 28, 2013.

Lenton, R., and M. Muller. 2009. Integrated Water Resources Management in Practice: Better Water Management for Development. London: Earthscan.

Lewis, W. M., Jr., and J. F. Saunders, III. 1989. Concentration and transport of dissolved and suspended substances in the Orinoco River. Biogeochemistry 7:203-240.

Lorino, M. R., Jr. 2011. Testimony before the U.S. Senate Environment and Public Works Committee, October 29, 2011. Online. Available at http://www.barpilot.com/news/testimony-by-michael-r-lorino-jr-before-the-senate-committee-on-environment-and-public-works/. Accessed June 27, 2013.

Loucks, D. P., and E. van Beek. 2005. Water Resources Systems Planning and Management. Paris: UNESCO.

Louisiana Coastal Wetlands Conservation and Restoration Task Force. 2013. West Bay Sediment Diversion (MR-03). Online. Available at http://lacoast.gov/reports/gpfs/MR-03.pdf. Accessed June 27, 2013.

Lower Mississippi Region Comprehensive Study Coordinating Committee. 1974-1975. Lower Mississippi Region Comprehensive Study. 7 vols. Vicksburg: USACE.

Ludy, J., and G. M. Kondolf. 2012. Flood risk perception in lands "protected" by 100-year levees. Natural Hazards 61:829-842.

Maass, A., M. Hufschmidt, R Dorfman, H. A. Thomas, Jr., S. Marglin, and G. M. Fair. 1962. Design of Water-Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Government Planning. Cambridge, MA: Harvard University Press.

Meade, R. H. ed. 1995. Contaminants in the Mississippi River, 1987-1992. U.S. Geological Survey Circular 1133. U.S. Department of the Interior. Denver, CO: U.S. Geological Survey.

Meade, R. H., and J. A. Moody. 2010. Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940-2007. Hydrological Processes 24:5-49. Online. Available at http://onlinelibrary.wiley.com/doi/10.1002/hyp.7477/pdf. Accessed June 11, 2013.

Mesehle, E., J. A. Corquodale, J. Sheldon, M. Dortch, S. Brown, M. Davis, Z. Wang, P. Elkan, and J. Schindler. 2012a. Appendix D-1 Eco-Hydrology Model Technical Report. Louisiana 2012 Coastal Master Plan. Baton Rouge, LA.

Meselhe, E. A., I. Georgiou, M. A. Allison, and J. A. McCorquodale. 2012b. Numerical modeling of hydrodynamics and sediment transport in lower Mississippi at a proposed delta building diversion. Journal of Hydrology 472–473(November):340-354.

Meyer, H., D. Morris, and D. Waggoner, eds. 2009. Dutch Dialogues: New Orleans, Netherlands. Common Challenges in Urbanized Deltas. Amsterdam: SUN.

Meyer, W. B., K. W. Butzer, T. E. Downing, G. W. Wenzel, J. L. Wescoat, and B. L. Turner, II. 1998. Reasoning by analogy. Pp. 217-290 in Human Choice and Climate Change: Tools for Policy Analysis, S. Rayner and E. Malone, eds. Columbus: Battelle Press.

Milliman, J. D., and R. H. Meade. 1983. World-wide delivery of river sediment to the ocean. Journal of Geology 91:1-21.

Milly, P. C. D., and K. A. Dunne. 2001. Trends in evaporation and surface cooling in the Mississippi River Basin. Geophysical Research Letters 28. Online. Available at http://onlinelibrary.wiley.com/doi/10.1029/2000GL012321/abstract. Accessed August 12, 2013.

Milly, P. C. D., J. Betancourt, M. Falkinmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? Science 319(5863):573-574.

Mintzberg, H. 2007. Tracking Strategies: Towards a General Theory of Strategy Formation. Oxford: Oxford University Press.

Mitchell, B. 1990. Integrated Water Management. New York: John Wiley.

Mitchell, B. 2006. IWRM in Practice: Lessons from Canadian Experiences. Universities Council on Water Resources. Journal of Contemporary Water Research and Education 135:51-55.

MIT Humanitarian Logistics. 2013. MIT Humanitarian Response Lab. Online. Available at http://humanitarian.mit.edu/. Accessed July 3, 2013.

Mithen, S. 2012. Thirst: Water and Power in the Ancient World. Cambridge: Harvard University Press.

Mollinga, P., and D. Gondelekhar. 2012. Theorizing structured diversity: An approach to comparative research on water resources management. ICCWaDS Working Paper 1.

Mollinga, P., A. Dixit, and K. Athukorala, eds. 2006. Integrated Water Resources Management. Global Theory, Emerging Practice and Local Needs. Water in South Asia series 1. New Delhi: Sage.

Montagna, P. A., and C. Ritter. 2006. Direct and indirect effects of hypoxia on benthos in Corpus Christi Bay, Texas, USA. Journal of Experimental Marine Biology and Ecology 330:119-131.

Mukerjee, R. 1938. The Changing Face of Bengal: A Study in Riverine Economy. Calcutta: University of Calcutta.

NASA (National Aeronautics and Space Administration). 2013. Earth Observatory. Online. Available at http://earthobservatory.nasa.gov/IOTD/view.php?id=7079. Accessed July 2, 2013.

Natural Hazards Center (University of Colorado, Natural Hazards Research Application and Information Center). 2013. Quick Response Grant Program. Online. Available at http://www.colorado.edu/hazards/research/qr/. Accessed July 1, 2013.

NOAA. 2013. Tides and Currents: Regional Mean Sea Level Trends. Online. Available at http://tidesandcurrents.noaa.gov/sltrends/slrmap.html. Accessed July 2, 2013.

Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe. 2007. Coastal systems and low-lying areas. In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson, eds. Cambridge: Cambridge University Press.

NRC (National Research Council). 1996. River Resource Management in the Grand Canyon. Washington, DC: National Academy Press.

NRC. 1999. Downstream: Adaptive Management of Glen Canyon Dam and the Colorado River Ecosystem. Washington, DC: National Academy Press.

NRC. 2002. The Missouri River Ecosystem: Exploring the Prospects for Recovery. Washington, DC: National Academy Press.

NRC. 2004. Adaptive Management for Water Resources Project Planning. Washington, DC: National Academies Press.

NRC. 2006. Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana. Washington, DC: National Academies Press.

NRC. 2009. The New Orleans Hurricane Protection System: Assessing pre-Katrina Vulnerability and Improving Mitigation and Preparedness. Washington, DC: National Academies Press.

NRC. 2011a. Missouri River Planning: Recognizing and Incorporating Sediment Management. Washington, DC: National Academies Press.

NRC. 2011b. Approaches for Ecosystem Services Valuation for the Gulf of Mexico After the Deepwater Horizon Oil Spill. Washington, DC: National Academies Press.

NRC. 2012. Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: National Academies Press.

New Orleans Times Picayune. June 17, 2013. St. Bernard and Plaquemines Parish fishers condemn state officials' and scientists' assessment. Online. Available at http://www.nola.com/environment/index.ssf/2013/06/st_bernard_and_plaquemines_par.html. Accessed June 19, 2013.

NUWCReN. 2012. Flood Preparedness in the Netherlands: A U.S. Perspective. Delft, The Netherlands: Deltares.

Odum, E. P. 1969. The strategy of ecosystem development. Science 164:262-270.

Odum, E. P. 1971. Fundamentals of Ecology. 3rd ed. Philadelphia, PA: W.B. Saunders.

Orlove, B., and S. C. Caton. 2010. Water sustainability: Anthropological approaches and prospects. Annual Review of Anthropology 39:401-415. Online as a Review in Advance on June 21, 2010. Available at DOI: 10.1146/annurev.anthro.012809.105045. Accessed August 12, 2013.

Ostrom, E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge: Cambridge University Press.

Ostrom, E. 2005. Understanding Institutional Diversity. Princeton: Princeton University Press.

Overeem, I., and J. P. M. Syvitski. 2009. Dynamics and Vulnerability of Delta Systems. LOICZ reports and studies, no. 35. Geesthacht, Germany: GKSS Research Center.

Paola, C., R. R. Twilley, D. A. Edmonds, W. Kim, D. Mohrig, G. Parker, E. Viparelli, and V. R. Voller. 2011. Natural processes in delta restoration: Application to the Mississippi Delta. Annual Review of Marine Science 3:67-91.

Pijnappels, M., F. Pater, and O. van Steenis. 2010. Deltas in Times of Climate Change: Connecting World Science and Deltas. Meeting Report. Rotterdam. Online. Available at http://www.climatedeltaconference.org/. Accessed August 12, 2013.

Port of New Orleans. 2013. About the Port of New Orleans. Available at http://portno.com/about. Accessed July 30, 2013.

Rabalais, N. N., and R. E. Turner. 2006. Oxygen depletion in the Gulf of Mexico adjacent to the Mississippi River. Pp. 225-245 in Past and Present Marine Water Column Anoxia, L. N. Nertetin, ed. NATO Science Series: IV-Earth and Environmental Sciences.

Rabalais, N. N., R. E. Turner, B. K. Sen Gupta, D. F. Boesch, P. Chapman, and M. C. Murrell. 2007. Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate and control hypoxia? Estuaries and Coasts 30:753-772.

Ragin, C. C. 1987. The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies. Berkeley: University of California Press.

RAND. 2011. Reducing future flood damage in New Orleans through home elevation and land use changes. Pardee RAND Graduate School. Online. Available at http://www.rand.org/content/dam/rand/pubs/research_briefs/2011/RAND_RB9612.pdf. Accessed July 30, 2013.

Reed, D. J. 2013. The regional context of integrated water resources management. Presentation to NRC Committee on Strategic Research for Integrated Water Resources Management, Baton Rouge, April 25.

Reed, D. J., and B. Yuill. 2009. Understanding subsidence in coastal Louisiana. Report to the Louisiana Coastal Area Science and Technology Program, University of New Orleans.

Reinhard, S., and H. Folmer. 2009. Water Policy in the Netherlands, Integrated Management in a Densely Populated Delta. Washington, DC: RFF Press.

Renaud, F. G., and C. Kuenzer. 2012. The Mekong Delta System: Interdisciplinary Analyses of a River Delta. Springer environmental science and engineering. New York: Springer.

Rijkswaterstaat. 2005. Management of Shorefront Hazards in the USA: Lessons for the Dutch Ministry of Transport, Public Works and Water Management. Utrecht, The Netherlands: Rijkswaterstaat.

Roberts, H. H., and J. M. Coleman. 2003. A 50-year history of Coastal Studies Institute contributions to science. Gulf Coast Association of Geological Societies/Gulf Coast Section SEPM. Transactions 53:704-720.

Rogers, P. P., P. Lydon, D. W. Seckler; United States Agency for International Development, Bureau for Asia and the Near East, Office of Technical Resources; Irrigation Support Project for Asia and the Near East. 1989. Eastern Waters Study: Strategies to Manage Flood and Drought in the Ganges-Brahmaputra Basin. Arlington, VA: ISPAN Technical Support Center.

Ryan, B. D. 2012. Design after Decline: How America Rebuilds Shrinking Cities. Philadelphia: University of Pennsylvania Press.

Ryan, T. P. 2012. The Economic Impact of Reduced Dredging of the Mississippi River. Online. Available at http://www.americaswetland.com/photos/OFFICIAL_Dr_Ryan_Final_Report_1_10_12.pdf. Accessed August 12, 2013.

Saito, Y., Z. Yang, and K. Hori. 2001. The Huanghe (Yellow River) and Changjiang (Yangtze River) deltas: A review on their characteristics, evolution and sediment discharge during the Holocene. Geomorphology 41:219-231.

Schenk, C. J. 2012. An estimate of undiscovered conventional oil and gas resources of the world, 2012. Available at http://www.usgs.gov/science/cite-view.php?cite=2931. Accessed August 12, 2013.

Sevier, M. B., D. Reed, C. Curole; Terrebonne Parish Local Coastal Program Advisory Committee; Rodney E. Emmer and Associates. 2000. Terrebonne Parish Local Coastal Zone Management Program. Houma, LA: Terrebonne Parish Consolidated Government, Department of Planning & Economic Development, Coastal Zone Management Division.

Shallat, T. 1994. Structures in the Stream: Water, Science, and the Rise of the U.S. Army Corps of Engineers. Austin: University of Texas Press.

Sidi, F. H., D. Nummedal, P. Imbert, H. Darman, and H. W. Posamentier. 2003. Tropical Deltas of Southeast Asia: Sedimentology, Stratigraphy and Petroleum Geology. Society for Sedimentary Geology Special Publication Number 76.

Simonovic, S. 2009. Managing Water Resources: Methods and Tools for a System Approach. Paris: UNESCO.

Sklar, L. 1992. Technical Review of the Bangladesh Flood Action Plan. Berkeley, CA: International Rivers Network.

Slack, T., et al. 2009. Poverty in the Texas Borderland and Lower Mississippi Delta: A comparative analysis of differences by family type. Demographic Research 20(15):353-376.

State of the Coast. 2010. 1st Biennial State of the Coast Conference Proceedings. Online. Available at http://www.stateofthecoast.org/. Accessed July 3, 2013.

State of the Coast. 2012. 2nd Biennial State of the Coast Conference Proceedings. Online. Available at http://www.stateofthecoast.org/. Accessed July 3, 2013.

Syvitski, J. P. M., A. J. Kettner, I. Overeem, E. W. H. Hutton, M. T. Hannon, G. R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, and R. J. Nicholls. 2009. Sinking deltas due to human activities. Nature Geoscience 2(10):681-686.

The Water Institute of the Gulf. 2013a. FAQs. Online. Available at http://thewaterinstitute.org/about/faqs/. Accessed July 4, 2013.

The Water Institute of the Gulf. 2013b. Our Staff. Online. Available at see: http://thewaterinstitute.org/who-we-are/staff/. Accessed July 4, 2013.

Thompson, B. 2012. A federal act to promote integrated water management: Is the CZMA a useful model? Environmental Law 42:201-240.

Timmerman, J., C. Pahl-Wostl, and J. Möltgen, eds. 2008. The Adaptiveness of IWRM: Analysing European IWRM Research. London: IWA.

Turner, R. E. 1987. Relationship between Canal and Levee Density and Coastal Land Loss in Louisiana. Washington, DC: U.S. Department of the Interior.

Turner, R. E. 2011. Beneath the salt marsh canopy: Loss of soil strength with increasing nutrient loads. estuarine coasts, 34. Online. Available at doi:10.1007/s12237-010-9341-y. Accessed August 12, 2013.

Turner, R. E., and N. N. Rabalais. 1991. Changes in Mississippi River water quality this century:Iimplications for coastal food webs. BioScience 41:140-148.

Turner, R. E., N. Quereshi, N. N. Rabalais, Q. Dortch, D. Justic, R. F. Shaw, and J. Cope. 1998. Fluctuating silica:nitrate ratios and coastal plankton food webs. Proceedings National Academy of Sciences 95:13,048-13,051.

Turnipseed, D. P . 2013. Predicting drivers and management practices in large river deltas: the USGS Delta Research and Global Observation Network (DRAGON). Presentation to NRC Committee on Strategic Research for Integrated Water Resources Management, Baton Rouge, April 25.

Tvedt, T. 2006-2013. History of Water Series. Six volumes to date. London: I.B. Tauris.

Unie van Waterschappen. 2013. Website of the (Dutch) Association of Water Authorities. Available at http://english.uvw.nl. Accessed August 6, 2013.

UNESCO (United Nations Economic, Scientific, and Cultural Organization). 2013. World Heritage List: Danube Delta. Online. Available at http://whc.unesco.org/en/list/588/. Accessed July 31, 2013.

U.N. Water. 2012. Status Report on The Application of Integrated Approaches to Water Resources Management. Available at http://www.unwater.org/downloads/UN-Water_Report_for_Rio_Flyer.pdf. Accessed August 12, 2013.

USACE (U.S. Army Corps of Engineers). 2011. MR&T 2011 Post Flood Report. Online. Available at http://www.mvd.usace.army.mil/Portals/52/docs/regional_flood_risk_management/Docs/SectionII-MRTProject.pdf. Accessed August 12, 2013.

USACE. 2013a. Mississippi River and Tributaries Project. Online. Available at http://www.mvd.usace.army.mil/About/MississippiRiverCommission (MRC)/MississippiRiverTributariesProject(MRT).aspx. Accessed June 27, 2013.

USACE. 2013b. Shared Vision Planning. Online. Available at http://www.sharedvisionplanning.us/resCase.cfm. Accessed July 31, 2013.

U.S. Department of Homeland Security. 2013. Lessons Learned: Social Media and Hurricane Sandy. Virtual Social Media Working Group and DHS First Responders Group. Available at http://www.naseo.org/Data/Sites/1/documents/committees/energysecurity/documents/dhs_vsmwg_lessons_learned_social_media_and_hurricane_sandy_formatted_june_2013_final.pdf. Accessed August 12, 2013.

U.S. DOT (U.S. Department of Transportation). 2013. Bureau of Transportation Statistics. National Transportation Statistics. Online. Available at http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html. Accessed June 27, 2013.

USGS. 2013. Forecast Mekong. Online. Available at http://deltas.usgs.gov/fm/. Accessed June 11, 2013.

U.S. House of Representatives. 2004. United States and the Iraqi Marshlands: An Environmental Response. Washington, DC: U.S. House of Representatives.

Van Beek, E. 2013. IWRM in Rhine and Danube deltas. Presentation to NRC Committee on Strategic Research for Integrated Water Resources Management, Baton Rouge, April 25.

Van der Most, H., M. Marchland, T. Bucks, T. Nauto, and M. van Staren. 2009. Adaptation to Climate Change—Another Challenge in the Sustainable Development of Deltas. Delft, The Netherlands: Deltares.

Vanden Bossche, J.-P., and G. M. Bernacsek. 1990. Source book for the inland fishery resources of Africa: 2. CIFA Technical Paper No.18.2. Rome: FAO. 411 pp.

Verduijn, S. H., S. V. Meijerink, and P. Leroy. 2012. How the Second Delta Committee set the agenda for climate adaptation policy: A Dutch case study on framing strategies for policy change. Water Alternatives 5(2):469-484.

Vermaat, J. E., L. M. Bouwer, W. Salomons, and R. K. Turner. 2005. Managing European Coasts. Dordrecht: Springer.

Vermaat, J. E., and M. A. Eleveld. 2013. Divergent options to cope with vulnerability in subsiding deltas. Climatic Change 117:31-39.

Vörösmarty, C .J., J. P. M. Syvitski, J. Day, A. de Sherbinin, L Giosan, and C. Paola. 2009. Battling to save the world's river deltas. Bulletin of the Atomic Scientists 65:31-43.

Werner, B. T., and D. E. McNamara. 2007. Dynamics of coupled human-landscape systems. Geomorphology 91:393-407.

Wescoat, J. L., Jr. 2000. Watersheds in regional planning. Pp. 147-171 in The American Planning Tradition: Culture and Policy, R. Fishman, ed. Washington, DC: Wilson Center, Smithsonian Institution.

Wescoat, J. L., Jr. 2009. Comparative international water research. Universities Council on Water Resources. Journal of Contemporary Water Research & Education 142:1-6.

Wesselink, A. J. 2007. Flood safety in the Netherlands: The Dutch response to Hurricane Katrina. Technology in Society 29(2):239-247.

Weston, N. B., R. Dixon, and S. B. Joye. 2006. Microbial and geochemical ramifications of salinity intrusion into tidal freshwater sediments. Journal of Geophysical Research: Biogeosciences 111:(G1):G01009, 10.1029/2005JG00007.

White, G. F. 1945. Human Adjustment to Floods. Chicago: University of Chicago Press.

White, G. F. 1957. A perspective of river basin development. Law and Contemporary Problems 22(2):157-184.

White, G. F. 1974. Natural Hazards: Local, National, Global. New York: Oxford University Press.

White, G. F. 1998. Reflections on the 50-year international search for integrated water management. Water Policy 1:21-27.

WRI (World Resources Institute). 2010. World hypoxic and eutrophic coastal areas. Online. Available at http://www.wri.org/files/wri/images/world_21dec2010.preview.jpg. Accessed July 3, 2013.

Woolley, D., and L. Shabman. 2008. Decision-Making Chronology for the Lake Pontchartrain & Vicinity Hurricane Protection Project. Final Report for the Headquarters, U.S. Army Corps of Engineers. Submitted to The Institute for Water Resources of the U.S. Army Corps of Engineers. Washington, DC: U.S. Government Printing Office.

Wright, L. D., J. M. Coleman, and M. W. Ericson. 1974. Analysis of Major River Systems and their Deltas: Morphologic and Process Comparisons. Technical Report, vol. 156. Baton Rouge, LA: Coastal Studies Institute, Louisiana State University.

Yang, S. L., J. Zhang, J. Zhu, J. P. Smith, S. B. Dai, A. Gao, and P. Li. 2005. Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response. Journal of Geophysical Research 110(F03006).

Zaninetti, J., and C. E. Colten. 2012. Shrinking New Orleans. Urban Geography 33(5):675-669.

Zhao, J., T. S. Bianchi, X Li, M. A. Allison, P. Yao, and Z. Yu. 2012. Historical eutrophication in the Changjiang and Mississippi delta-front estuaries: Stable sedimentary chloropigments as biomarkers. Continental Shelf Research 47:133-144.

Appendix A

Guest Speakers at Committee Meetings

The Water Institute of the Gulf
Charles Groat, Executive Director
Denise Reed, Chief Scientist

Federal Agencies
John Ettinger, U.S. Environmental Protection Agency, Baton Rouge
Richard Hartman, NOAA Fisheries, Baton Rouge
Philip Turnipseed, U.S. Geological Survey, Lafayette

Louisiana Universities
Michael Blum, Tulane University, New Orleans
Mark Davis, Tulane University, New Orleans
Chris D'Elia, Louisiana State University, Baton Rouge
Nancy Rabalais, Louisiana Universities Marine Consortium, Chauvin
Robert Twilley, Louisiana State University, Baton Rouge

State of Louisiana
Kyle Graham, Coastal Protection and Restoration Authority, Baton Rouge

Nonprofit Organizations, Other Universities
Seth Blitch, The Nature Conservancy, Baton Rouge
Donald Boesch, University of Maryland Center for Environmental Studies, Cambridge
Robert Dalrymple, Johns Hopkins University, Baltimore
John Lopez, Lake Pontchartrain Foundation, Baton Rouge
Matt Rota, Gulf Restoration Network, New Orleans

Appendix B

Biographical Sketches of Committee Members and Staff

James L. Wescoat, *Chair*, is the Aga Khan Professor in the Department of Architecture at the Massachusetts Institute of Technology. He was previously the head of landscape architecture at the University of Illinois at Urbana-Champaign, and a professor in the Department of Geography, University of Colorado. His research has concentrated on water systems in South Asia and the United States from the site to river basin scales. He has conducted water policy research in the Colorado, Indus, Ganges, and Great Lakes basins, including the history of multilateral water agreements. He is currently conducting comparative international research on water hazards and conservation innovations in the United States, South Asia, and Central Asia. Dr. Wescoat has served on and chaired several NRC Committees, most recently the Committee on Himalayan Glaciers, Climate Change, and Implications for Downstream Populations. He received his B.L.A. degree in landscape architecture from Louisiana State University and his M.A. and Ph.D. degrees in geography from the University of Chicago.

Ximing Cai is an associate professor and Ven Te Chow Faculty Scholar in Water Resources in the Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign (UIUC). Before joining UIUC, he worked as a joint research fellow at the International Food Policy Research Institute and the International Water Management Institute. His current research areas include water-energy system analysis, coupled human-natural systems modeling, and sustainable infrastructure system analysis. In particular he has been conducting integrated hydrological-ecological- economic modeling analysis for large-scale river basins, addressing the interactions and coevolution of human and natural systems, and providing policy implications for sustainable river basin management in the United States and around the world. Dr. Cai has worked as a consultant to the World Bank, the United Nations, and the OECD to solve international water resources management problems. He holds a Ph.D. degree in civil dngineering from the University of Texas at Austin.

Ben R. Hodges is an associate professor of civil engineering at the University of Texas at Austin. His primary areas of interest are in the fields of environmental fluid mechanics and surface water hydraulics; coupled field and model investigations of hydrodynamics in lakes, rivers, and estuaries; relationships between river hydraulics and instream flow for aquatic habitat; and linkages between water quality and hydrodynamics in natural systems. His recent research has focused on hydrodynamic and transport modeling of the stratification in Corpus Christi Bay, which impacts episodic hypoxia development. He was a member of the NRC Committee to Review the St. Johns River Water Supply Impact Study. Dr. Hodges received his B.S. degree in marine engineering and nautical science from the U.S. Merchant Marine Academy, his M.S. degree in mechanical engineering from George Washington University, and his Ph.D. degree in civil engineering from Stanford University.

Samantha B. Joye is the Athletic Association Professor of Arts & Sciences in the Department of Marine Sciences at the University of Georgia. Her research program encompasses multiple fields of study, including biogeochemistry and microbial community structure and potential metabolic activity in coastal environments. In particular, she has focused on the cycling of nutrients, dissolved gases, trace metals, carbon, and sulfur in a variety of systems, ranging from saline lakes to temperate and tropical coastal environments to deep ocean sediments and brines to Antarctic lakes and Arctic seas. She has also studied how coastal ecosystems (in such regions as Georgia, South Carolina, Louisiana, and Massachusetts, as well as mangrove forests in Florida, Belize, and Panama) respond to global change and various natural and anthropogenic forcing functions. Finally she has been involved in determining how microbial and geochemical processes have responded to the 2010 Gulf of Mexico Deepwater Horizon incident. She received her B.S. and Ph.D. degrees from the University of North Carolina.

G. Mathias Kondolf is a professor at the University of California, Berkeley, where he serves as chair of the Department of Landscape Architecture and Environmental Planning. His research concerns human-river interactions broadly, with emphasis on management of flood-prone lands, sediment management in reservoirs and regulated river channels, and river restoration. Dr. Kondolf is currently analyzing cumulative sediment trapping from construction of proposed dams in the lower Mekong River basin and organizing a workshop on sediment starvation impacts on the Mekong delta. He is evaluating current riparian restoration efforts in the lower Colorado River and in the Klamath River basin. As Clarke Scholar at the Institute for Water Resources of the U.S. Army Corps of Engineers, he launched a review of nonstructural approaches to floodplain management, and he formerly served on the Environmental Advisory Board to the Chief of the Corps. He was also on the Science Board for the CALFED Bay-Delta Ecosystem Restoration Program. Dr. Kondolf served on the NCR Committee on Further Studies of Endangered and Threatened Fishes in the Klamath River. He received his A.B. degree in geology from Princeton University, his M.S. degree in earth sciences from the University of California, Santa Cruz, and his Ph.D. degree in geography and environmental engineering from Johns Hopkins University.

William M. Lewis, Jr., is professor of ecology and evolutionary biology, director of the Center for Limnology, and associate director of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. His research interests, as reflected in over 200 journal articles and books, include productivity and other metabolic aspects of aquatic ecosystems, aquatic food webs, composition of biotic communities, nutrient cycling, and the quality of inland waters. Dr. Lewis has worked not only in North America but also on tropical aquatic ecosystems of Latin America and Southeast Asia. His current research projects include use of models to estimate global primary production (carbon fixation) of lakes, nutrient regulation of algal populations in inland waters, and nitrogen cycling in inland waters. Dr. Lewis has served as a member or chair of numerous NRC committees; he was chair of the Committee on Endangered and Threatened Fishes in the Klamath River Basin, the Committee on Glen Canyon Environmental Studies Review, and the Committee on Wetlands Characterization. He received his Ph.D. degree from Indiana University.

Leonard A. Shabman is a Resident Scholar at Resources for the Future in Washington, DC. He previously was a professor of agriculture and applied economics in the Department of Agricultural Economics at the Virginia Polytechnic Institute and State University. Dr. Shabman's professional interests include economics, water resources, policy analysis, resource planning, wetlands, and pollution control. He also has served as an economic adviser to the (former) federal Water Resources Council and as scientific adviser to the assistant secretary of the army, Civil Works. Dr. Shabman is a past member of the NRC Water Science and Technology Board and has chaired several NRC committees, including the Committee on the Missouri River

Recovery and Associated Sediment Management Issues, the Committee to Assess the U.S. Army Corps of Engineers Methods of Analysis and Peer Review for Water Resources Project Planning, and the Committee on Mitigating Wetland Losses. Dr. Shabman received his Ph.D. degree in agricultural economics from Cornell University.

Eelco van Beek is a water resources specialist in the Netherlands, where he splits his time between three organizations. First, he is a part-time professor in the field of modelling integrated water resources management at the University of Twente where he is leading two multiparty research projects: (1) freshwater supply in delta areas under climate change and (2) perspectives in water management, aiming to integrate social/institutional and technical aspects in decision making under uncertainty. Second, he is a water resources management specialist at Deltares, where he is involved in the new Delta Plan for the Netherlands and participating as integrated water resources management expert in several delta projects around the world, in particular the Mekong, Ganges/Megna, and Ciliwung/Jakarta. Finally, for the Global Water Partnership he is presently involved in a scientific background paper on water security. He has been actively involved in many water resources development projects in the Netherlands and abroad, ranging from projects with emphasis on long-term planning to real-time operation, from projects aimed at pre-feasibility studies to detailed water management projects, and from integrated studies (water quantity, water quality, ecology, economics, socioeconomics, and institutional aspects) to single-aspect studies. He received his M.Sc. degree in civil engineering, *cum laude*, Delft University of Technology.