Missouri River Planning: Recognizing and Incorporating Sediment Management

Committee on Missouri River Recovery and Associated Sediment Management Issues; National Research Council

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COMMITTEE ON MISSOURI RIVER RECOVERY AND ASSOCIATED SEDIMENT MANAGEMENT ISSUES

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Preface

The U.S. Army Corps of Engineers built many of the dams and bank control structures that now control Missouri River hydrology and geomorphology. Operations of these projects, in conjunction with projects built by other entities, provide many benefits, including moderation of flood flows that allow human activity in once flood-prone areas, reliable supplies of hydroelectric power and water supply for rural and urban areas, a reliable commercial navigation channel, and extensive water-based recreation opportunities. Recent attention to the status of, and protection, for three endangered species has focused attention on a need to better understand the river's altered sedimentary processes and how these processes might be best managed in the interests of species recovery. Meanwhile, changes to sedimentary processes and river geomorphology threaten some benefits currently enjoyed by basin residents and water-related and other infrastructure along the river, and have been associated with the loss of wetlands along the Gulf coast.

In response to a request from the Corps of Engineers, the National Academies convened a committee to address seven questions related to Missouri River sediment. The topics covered by the questions ranged from a general overview of past and present sediment processes, to how current habitat construction projects and other sediment management alternatives might support species recovery, affect local water quality, as well as land building processes and water quality in the Gulf of Mexico. The committee thoroughly considered each question in its deliberations and spent a good deal of time discussing its consensus responses to them. Beyond specific findings and recommendations, two cross-cutting themes are reflected throughout this report.

First, understanding of sedimentary processes effects actions that result in changes to those processes and is increasingly important for future Missouri River management. Although ongoing studies are being conducted, there is a need to strengthen and synchronize historical and contemporary databases, while at the same time make management decisions under uncertainty. This report's findings and recommendations thus frequently stress the need for improved monitoring data collection, more rigorous interpretation and analysis and openness to learning over time even while decisions are made with limited understanding of the system. Second, the committee was attentive to the roles and responsibilities of technical analysts to inform, but not dictate, decisions made in the public choice process. The report's final chapter (7) offers perspectives on the role of the science community in future policy decisions on river management.

The committee acknowledges the National Research Council and its staff from the Water Science and Technology Board (WSTB) for their steadfast efforts in organizing the committee's activities during and between meetings throughout the study process. Their assistance has been both tireless and always cheerfully given. In particular, we appreciate the efforts of our study director, Jeffrey Jacobs, to debate and challenge the arguments being made, then carefully edit the committee's numerous and extensive draft reports. WSTB senior program associate Anita Hall expertly attended to administrative, logistics, and financial details of our meetings and assisted with editorial and related publications responsibilities.

We are grateful to the many individuals who shared their time and insights with this committee. Appendix A lists invited guest speakers at the committee's open, public meetings. The views of our invited speakers were complimented nicely by literally dozens of interested and active citizens who offered their comments during our public comment sessions. Our committee benefitted greatly in hearing from all of our speakers, who had unique points of view and backgrounds that were important in contributing to our collective understanding of today's important scientific and public policy issues along the Missouri River.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with the procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible, and to ensure that the report meets NRC 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 thank the following for their review of this report: Jim Best, University of Illinois; Patrick L. Brezonik, University of Minnesota; Martin W. Doyle, University of North Carolina; Charles G. Groat, University of Texas; Matt Kondolf, University of California; Nancy N. Rabalais, Louisiana Universities Marine Consortium; A. Dan Tarlock, Chicago-Kent College of Law; Peter R. Wilcock, Johns Hopkins University.

Although these reviewers provided constructive comments and suggestions, they were not asked to endorse the report's conclusions and recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Kenneth W. Potter, University of Wisconsin, who was appointed by the NRC Division on Earth and Life Studies. Dr. Potter was responsible for ensuring that an independent examination of this report was conducted in accordance with NRC institutional procedures and that all review comments were carefully considered. Responsibility for this report's final contents rests entirely with the authoring committee and the NRC.

Leonard A. Shabman, *Chairman*

Contents

Summary

The Missouri River long has been an integral tributary in North America's largest conveyance system—the Mississippi River system—for transporting sediment from interior uplands to the coastal ocean. During the twentieth century, the volumes of sediment transported downstream and to the Gulf of Mexico by these rivers were reduced markedly by numerous changes to river hydrology and sedimentary processes. During this period, several large mainstem dams were constructed across the Missouri River, along with numerous dams on the river's tributaries. Along with the dams, hundreds of miles of river channel engineering structures were built to facilitate commercial navigation. These channelization and bank stabilization projects fixed the river channel in place and supported a serviceable navigation channel from Sioux City, Iowa downstream to the Missouri River confluence near St. Louis. In doing so, the projects immobilized vast amounts of sediment, as portions of the former river channel and banks were converted into floodplain lands behind revetments and other structures.

The cumulative goals of the dam and the bank stabilization projects—flood control, hydropower generation, water supply, recreation, and a commercial navigation channel—have been realized. At the same time, these structures have sharply changed the river's sediment transport and deposition regime. These changes included large reductions in the volumes of sediment transported through the system, lowering of the river channel bed downstream of dams and along some channel reaches, reductions in turbidity, and changes in landforms and riverine habitat important to native biota.

These changes in Missouri River sediment processes have greatly affected near-shore and riparian habitats important to some native species. As a result, three of these species—two birds (the least tern and piping plover) and one fish (the pallid sturgeon)—today are listed under the federal Endangered Species Act. Changes to the river's sediment regime also are having impacts on important physical infrastructure. Channel bed lowering, for example, is eroding foundations of flood protection structures in and near Kansas City, and of bridge foundations at many sites along the river and its tributaries. Lower river levels also cause problems at intakes for municipal and industrial water supply systems along the river.

The U.S. Army Corps of Engineers oversees operations of the Missouri River mainstem reservoir system. The U.S. Fish and Wildlife Service issued Biological Opinions in 2000 and

2003 regarding Corps of Engineers projects and operations along the lower Missouri River (USFWS, 2000, 2003). In response to those Biological Opinions, the Corps has been constructing projects along the Missouri River designed to improve habitat conditions for the endangered bird and fish species. Project construction has been accompanied by sediment discharges into the lower Missouri River. Given the location of these Corps of Engineers habitat mitigation projects on lower Missouri River, much of this report thus focuses on the river's channelized portion from Sioux City, Iowa downstream to the confluence with the Mississippi River.

Discharges of sediment from these projects have prompted concerns regarding not only local water quality impacts, but also questions regarding delivery of sediments and nutrients to the Mississippi River delta and the northern Gulf of Mexico. One section of this report thus considers possible downstream effects on water quality into the northern Gulf of Mexico.

Sedimentary processes and sediment management issues are important along the entire length of the Missouri River. For example, large volumes of sediment are trapped in the Missouri River's upstream reservoirs and represent a substantial portion of sediment no longer available for transport to the Gulf of Mexico. Other sections of the report thus consider sediment processes, and data collection and evaluation systems, for the entire length of the river.

This report is from the National Research Council (NRC) *Committee on Missouri River Recovery and Associated Sediment Management Issues*. The study and report were sponsored by the U.S. Army Corps of Engineers. The committee was appointed in 2008 and held five meetings over the course of its project. Public meetings were convened in four Missouri River cities: St. Louis, Omaha, Vermillion, SD, and Kansas City. A final, closed meeting was held in Washington, D.C. in early 2010 at which the committee worked on its draft report.

This report addresses the topics of Missouri River sediment, its physical and biological importance, how its dynamics and roles in the river system have changed over time, and its roles in contemporary river management decisions. The committee was asked to address:

- the roles of Missouri River sediment in river ecology and restoration, and its implications for water quality and coastal restoration downstream in the northern Gulf of Mexico;
- environmental and economic considerations regarding nutrient and contaminant loadings;
- alternatives for reintroducing sediment into the system, and;
- current Corps of Engineers restoration actions as they relate to sediment and nutrients, and how they might be improved.

The committee's full statement of task appears in Chapter 1, Box 1-1.

This Summary is organized in parallel with the chapters of this report and contains the following sections: Changes in Missouri River Sediment and Related Processes; Missouri River Governance and Programs for Sediment Management; Missouri River Sediment Management and Ecological Resources; Missouri River Sediment Management Alternatives and Opportunities; Missouri River Water Quality, and Future River Management Decisions.

This report's findings and recommendations are presented in bold-faced text.

CHANGES IN MISSOURI RIVER SEDIMENT AND PROCESSES AND SUPPORTING DATA MANAGEMENT SYSTEMS

Roles of Sediment in the Missouri River

Question 1 of this report's statement of task asked "*How and why is sediment a significant variable in the environmental restoration of a river system like the Missouri River?"*

The processes of sediment erosion, transport, and deposition play important geomorphologic and ecological roles in large river systems. Sediments are important, for example, as foundational material for islands and sandbars that, in turn, provide animal and plant habitat. For some native fish species that evolved in highly turbid rivers like the Missouri, these conditions are important in inhibiting predation. In the Missouri and Mississippi River system, sediment from the Missouri River basin is eventually transported farther downstream by the Mississippi River and historically has been of great importance in sustaining wetlands in coastal Louisiana.

Sediment is a significant variable in environmental restoration of a river system like the Missouri River for the following reasons:

- **Most of the historical, pre-regulation Missouri River was a sediment-rich system. However, not all tributaries of the Missouri River were sediment-rich;**
- **For many river processes and services, sediment concentrations and transport are as important as the quantity and flow of water. For example, sediment is the basic building material for river landforms that, among other things, support habitats for native riverine flora and fauna;**
- **High concentrations of sediment and high turbidity in the pre-regulation river were important to the evolution and adaptation of native species such as the pallid sturgeon;**
- **Sediment delivered from the Missouri River to the Mississippi River was historically significant in building and sustaining coastal wetlands in the actively accumulating lobes of the Louisiana delta.**

The reduced volumes of sediment transported by the post-regulation Missouri River relate to Question 5 in this report's statement of task, which asked "*Are there long-term consequences to the lack of sediment in the system to the human environment, either economically or environmentally?"* (questions 1 and 5 are addressed in Chapter 2).

The Missouri River underwent a fundamental transformation during the mid-twentieth century. The mainstem and tributary dams, and the revetments and other river control structures built as part of the federal Bank Stabilization and Navigation Project (BSNP), helped control floods, generate hydroelectric power, provide reliable water supplies, and support commercial navigation. These projects resulted in major changes not only in river hydrology, but also in related sedimentary processes and volumes transported. The reduction of peak flood discharges, for example, reduced the river's ability to transport sediment downstream. The mainstem dams and reservoirs trapped large amounts of sediment that previously moved downstream. These changes have had many implications for river ecology, local infrastructure, and downstream sedimentary processes in coastal Louisiana.

The primary long-term consequences of a lack of sediment in the system are:

- **Reduced turbidity;**
- **Loss of habitat for some native species;**
- **Bed degradation downstream of dams and extensively along the main channel and the lower reaches of tributaries. This causes problems for infrastructure by undermining levees and bridge foundations and lowering water levels at municipal water intakes;**
- **Reduced volumes of sediments transported downstream to the Mississippi River and delivered to the Mississippi River delta region.**

Sediment Data Collection, Organization, and Analysis

The Missouri River basin once was the site of extensive scientific programs for sediment data collection and analysis. Over time, however, these programs received less emphasis and lower priority. Today, data on Missouri River sediment are diffuse and scattered across different agencies, in a variety of locations, and in different formats. There is no single system or center to ensure that data have been updated to be consistent with modern mapping, archiving, and other technologies and applications. Ongoing sediment data studies are being conducted by Corps of Engineers and U.S. Geological Survey scientists, and these are improving knowledge of sedimentary processes along the river. These efforts, however, are not being conducted as part of systematic sedimentary studies for the length of the river.

Thus, despite useful ongoing efforts, sediment data collection and management programs are fragmented and do not provide a reliable, accessible knowledge base for river managers, scientists, and interested members of the public. Along the river today, there are several relatively new river ecosystem management initiatives. For example, the Missouri River Recovery Program (MRRP), initiated in the mid-2000s, is being led by the Corps of Engineers and the U.S. Fish and Wildlife Service, in partnership with tribes, states, and other agencies, to develop and implement Missouri River ecosystem recovery actions. The MRRP, along with other new initiatives—including the Missouri River Ecosystem Restoration Program (MRERP) and the Missouri River Recovery and Implementation Committee (MRRIC)–are likely to be central in the coming decades of Missouri River ecosystem management decisions. As such, they will benefit from a coherent, detailed, and accessible database of sediment processes. Compared to databases and related science programs in other large river and aquatic systems that are sites of major ecosystem management activities–such as the Colorado River in the Grand Canyon and the Florida Everglades—data systems for the Missouri River and its ecosystem are less developed.

The systems and processes for evaluating, archiving, and retrieving Missouri River sediment data are fragmented and not well organized. These gaps are of special concern

given plans for future investments in Missouri River ecosystem management and re-evaluation of authorized purposes for the Missouri River mainstem dams and the Bank Stabilization and Navigation Project. Effective project implementation, operations and management requires useable knowledge of sediment dynamics, including quantities and fluxes of suspended and coarse bed loads, and changes in sediment storage and resultant changes in channel morphology. More informed future Missouri River resource management decisions will benefit from a comprehensive and accessible Missouri River sediment database and sediment budget.

Corps of Engineers and the U.S. Geological Survey scientists have been conducting valuable collaborative investigations of Missouri River sedimentary processes that should be used as the foundations for a more detailed and extensive sediment budget. Over time, continued collaboration may lead to a more formal program for data collection and evaluation. The Corps and the USGS should extend their collaborative efforts and develop a detailed Missouri River sediment budget for the headwaters to the river's mouth, with provisions for continuing revisions and updates as new data become available.

MISSOURI RIVER GOVERNANCE AND SEDIMENT MANAGEMENT

This section provides background for understanding Missouri River governance, especially as it relates to management of sediment and related resources. It also addresses question 7 in this report's statement of task regarding improved management strategies and actions (these topics are addressed in Chapter 3).

An important piece of legislation in the history of Missouri River operations is the Flood Control Act (FCA) of 1944. That act authorized the Corps of Engineers to construct Missouri River mainstem dams as part of the 'Pick-Sloan Plan', which represented a merger of plans between the Corps of Engineers and the U.S. Bureau of Reclamation. Under Pick-Sloan, the Corps constructed six mainstem dams in the 1950s and 1960s, and for many years had preeminent authority regarding their operations. The U.S. Congress today continues to create authorities and responsibilities that support the Corps of Engineers in this role as 'water master' of the Missouri River—and hence sediment manager—as well. At the same time, a flurry of new institutions and programs created in the past five years has broadened the decision-making context of Missouri River operations.

In 2007, the Congress authorized the Corps to execute the Missouri River Ecosystem Restoration Plan (MRERP), and in 2009 authorized the Corps to conduct the Missouri River Authorized Purposes Study (MRAPS). These two major programs are studying and guiding ecosystem recovery, and reviewing the authorized purposes of the Missouri River dam and reservoir system, respectively.

In addition to these programs, in 2007 the Secretary of the Army created the Missouri River Recovery and Implementation Committee (MRRIC). The MRRIC was established with broad representation of numerous basin stakeholders to promote shared Missouri River decision making. Although the MRRIC's roles have yet to be fully clarified, they will need to be defined with regard to Corps of Engineers authorities. The Missouri River states, tribes, commercial interests, and nongovernmental organizations all seek a more active voice and role in river management decisions. At the same time, the Corps retains authority to operate the Missouri River dam and reservoir system. Furthermore, several recent, major river management initiatives and studies—such as the 2000/03 Biological Opinion and the mitigation program—have added greatly to compliance requirements for the Corps. These changes have complicated the Missouri River governance structure for the Corps and others as they try to reach agreement on programs such as Biological Opinion program implementation, broader ecosystem recovery, and sediment management planning.

The Missouri River Recovery and Implementation Committee has the potential to play a central role in building consensus among a broad group of federal agencies and stakeholders in matters related to water and sediment management. To help realize that potential, the Secretary of the Army should periodically review the MRRIC mission statement, operational rules and accomplishments, implement modifications to the mission, rules and operations as deemed appropriate, and report its results to the Congress.

MISSOURI RIVER SEDIMENT AND ECOLOGICAL RESOURCES

Question 7 in this report's statement of task asked *"Are current Corps management strategies, restoration tools (e.g., channel widening, creation of chutes, shallow water habitat, etc.) and other activities adequate and comprehensive enough to address issues associated with sediment and nutrients in the system? If not, how might such strategies and activities be improved?"* (this question is addressed in Chapter 4).

The Corps of Engineers has been constructing numerous Emergent Sandbar Habitat (ESH) and Shallow Water Habitat (SWH) projects along the Missouri River in compliance with the 2000/03 Fish and Wildlife Service Biological Opinion. The Biological Opinion directs the Corps to implement and operate those projects according to adaptive management principles. In addition to project construction, the Corps has been monitoring these projects and has been developing adaptive management guidance documents. The emergent sandbar habitat and shallow water habitat projects are being implemented as part of and within the larger Missouri River Recovery Program (MRRP) and they have important ecological and institutional linkages with other MRRP programs for ecosystem recovery.

To date, the Corps of Engineers ESH and SWH projects have been implemented and monitored with only limited strategic guidance and have not been part of a systematic, long-term adaptive management program. The reversal or slowing of declines of endangered and threatened bird and fish species cannot be accomplished immediately. Similarly, management of sediments and nutrients associated with these projects will be an ongoing, long-term process that will be affected and guided by new scientific information, possible changes in laws and water quality standards, and shifting social preferences regarding Missouri River management and resources.

If a more systematic form of adaptive management is to be developed and applied to Missouri River ecosystem, sediment, and related resources management, it will entail more

than development of appropriate guidance documents. At a minimum, it will require a sustained commitment of resources for monitoring and science programs, stakeholder participation and discussions, expert input and advice, and patience in working with large ecological systems and species that do not respond quickly or predictably to management actions.

If federal agencies and others are to implement a more structured adaptive approach to habitat and broader ecosystem restoration, those efforts will be more effective to the extent they are founded on the following:

Develop performance objectives that are tied to ecological and biological variables and designed to determine if compliance actions are reducing jeopardy to listed species.

There is a need to expand on the "acres created" metric used by the Corps of Engineers for mitigation projects along the river. Development of indicators more closely linked to life cycles of the endangered species should better determine the degree of project success.

Develop conceptual ecological models (CEM) for the three endangered species that will consider and evaluate all variables that affect reproduction and survival.

Development and refinement of these types of models will allow for testing of multiple hypotheses regarding environmental variables and their influences on life cycles, recruitment, and regeneration.

Ensure that ecosystem monitoring is targeted to testing of hypotheses derived from the conceptual models, and that findings are used to further refine the models and gauge progress toward attaining management goals.

Monitoring that has been conducted to date has been extensive and can form a good platform for future evaluation. There will, however, have to be a stronger link between monitoring, and subsequent evaluation in order to help determine if management objectives are being met. It also will be important to ensure that ecosystem monitoring is clearly and strongly tied to the central components of a clearly defined management agenda.

Explicitly assess progress of relevant MRRP programs towards achieving the 2000/03 Biological Opinion goal of reducing jeopardy to the three listed species.

Corps management strategies to address sediment and nutrient issues in the Missouri River are undertaken through multiple interdependent programs within the MRRP under their Biological Opinion compliance responsibilities as directed by the U.S. Fish and Wildlife Service reasonable and prudent alternatives (RPA). An essential element of adaptive management is to review management actions in light of new information from monitoring and assessment programs, and to revise management alternatives as needed. An adaptive management process requires confirming that existing management actions are necessary and adequate for contributing to species recovery, or if MRRP program elements or Biological Opinion reasonable and prudent alternatives need to be adjusted based on evaluation of results and what has been learned.

The ultimate outcomes of these site-level projects, and whether they will result in jeopardy status being removed for endangered bird and fish species, are not known—nor will they be known for years. Adaptive management principles would dictate that, in addition to these ongoing projects, consideration be given to alternatives that might be implemented if ESH and SWH project objectives are not achieved.

Given the uncertainties associated with outcomes from Corps of Engineers Emergent Sandbar Habitat and Shallow Water Habitat programs, it is possible that they may not meet requirements of the Biological Opinion to avoid jeopardizing the continued existence of the tern, plover, and sturgeon. The ESH and SWH programs, and the suite of new Missouri River system initiatives and studies, thus should formulate alternative actions that eventually may need to be implemented to increase the likelihood of species recovery.

MISSOURI RIVER SEDIMENT MANAGEMENT ALTERNATIVES AND OPPORTUNITIES

Question 6 from this report's statement of task asked, *Are there alternatives for reintroducing sediment into the system? What are they and what are the key constraints surrounding these alternatives?"*

Question 3 in the statement of task asked asked *"What is the significance of the Missouri River sediments to the restoration of Louisiana coastal wetlands?"*
(both questions are addressed in Chapter 5).

The Corps is implementing its ESH and SWH projects consistent with reasonable and prudent alternatives as specified in the 2000/03 Biological Opinion. These projects aim to restore a portion of some features of the pre-regulation Missouri River to help protect endangered bird and fish species. High turbidity was a prominent feature of the pre-development Missouri River. Along with local sediment implications of these projects, parties downstream in Louisiana are interested in the prospects for increasing the volumes of sediment delivered from the Missouri River to Louisiana in hopes of slowing or reversing losses of coastal wetlands.

Sediment Reintroduction Alternatives and Constraints

Primary alternatives that might be employed to re-introduce additional sediment into the Missouri River are: removing bank stabilization and control structures; commercial dredging; bypassing sediment around mainstem dams; dam removal; and increasing sediment from tributaries.

Implementation of any of these alternatives would be constrained by financial, technical, and other factors. A major constraint on any alternative is the degree to which current economic activities, transportation infrastructure, water quality, and public safety depend on the existing system of dams and river bank control structures. It is not likely that major reconfiguration of the river channel, or removal of a large dam, would be desirable or acceptable to a large majority of Missouri River valley residents in the near future.

Bypassing of large amounts of sediment around Gavins Point Dams may be technically feasible. This option, however, would be expensive and have little potential to significantly re-establish pre-regulation supplies of sediment that were delivered to Louisiana. Substantially increased contributions of sediment from large tributaries to the Missouri River downstream from Gavins Point Dam, such as the Kansas River, are unlikely under present sediment management rules because these rivers have their own large storage reservoirs.

Implications for Coastal Louisiana

Before 1900, the Missouri and Mississippi Rivers system transported an estimated annual average of 400 million metric tons of sediment from the interior United States to coastal Louisiana. From 1987-2006, this transport averaged 145 million metric tons per year. This annual sediment "deficit" thus is on the order of roughly 250 million metric tons per year. Some of the sediments previously delivered downstream are trapped in Missouri River reservoirs, while some of the sediments have been immobilized by river engineering activities and structures such as meander cutoffs and riverbank revetments.

If all the sediment excavated for the Corps of Engineers' shallow water habitat projects were to be delivered to the channel, the added sediment would equal about 34 million tons/year. This would represent roughly a 10-20 percent increase in sediment delivered to Louisiana for at least the next 15 years, depending on the trapping efficiency of the Mississippi floodplain. This figure is less than the annual 250 million ton 'deficit.' The bypassing of sediment from Lewis and Clark Lake around Gavins Point Dam would at best increase the supply of wetland constructing sediment to the Mississippi delta by only a few percent. Other prospects for mobilizing sediment in the Missouri and its tributaries are more likely to have local effects on bar building and local channel mobility than to contribute significantly to wetland construction in the Mississippi delta.

The amounts of sediment likely to be available for transport from the Missouri River to the Mississippi River delta are smaller than the quantities that made the journey before the construction of mainstem dams and implementation of the major bank stabilization structures.

MISSOURI RIVER WATER QUALITY

Question 2 in this report's statement of task asked, *"What is the significance of the Missouri River sediments to the Gulf of Mexico hypoxia problem?"*

Question 5 in this report's statement of task asked, *"What are the key environmental and economic considerations regarding nutrient loads and/or contaminants in Missouri River sediment? To what extent can such issues be addressed with management strategies?"* (both questions are addressed in Chapter 6).

Corps of Engineers emergent sandbar habitat (ESH) and shallow water habitat (SWH) projects are sites where sediment is being directly deposited into the mainstem Missouri River. Concerns have been expressed regarding the potential water quality impacts of those projects downstream into the northern Gulf of Mexico.

An upper bound estimate of the increase in phosphorus loadings to the Gulf as a result of the Corps SWH projects is a 6-12 percent increase. Similarly, an upper bound estimate of the downstream deliveries of bypassing sediment around Gavins Point Dam is that the additional sediment would increase total phosphorus load by roughly 1-2 percent. Both these estimates represent upper bounds. In reality, sediment deposition processes in the Missouri and Mississippi River channels would reduce loads delivered to the Gulf, and actual downstream deliveries would be less than these values.

A comparison of potential phosphorus loads from Corps SWH projects, with load increments required to produce measureable changes in the areal extent of Gulf hypoxia, shows that these projects will not significantly change the extent of the hypoxic area in the Gulf of Mexico. Additional comparisons of other alternatives for reintroducing sediment to the river—namely, bypassing sediment around Gavins Point Dam—yield a similar conclusion that they will not significantly change the areal extent of the hypoxic zone.

There also have been questions regarding annual areal changes in the hypoxic zone in the northern Gulf of Mexico, and the relations of these changes with sediment loadings from the Corps ESH and SWH projects along the Missouri River.

In addition to nutrient loadings, multiple factors—including meteorologic, hydrodynamic, and timing factors—affect the size of the hypoxic zone each year. Given the relatively small volumes of sediment loadings from the Corps' Missouri River ESH and SWH projects, it is not appropriate to relate changes in the areal extent of the hypoxic zone to sediment and nutrient loadings from Missouri River ESH and SWH projects in any given year.

The sediment that was essential to pre-regulation river morphology and landforms, and to the turbidity that supported the ecosystem of native species, had certain characteristics. Development of narrative or numeric water quality criteria that is sensitive to these historic conditions will consider such factors in setting limits on sediment, as well as phosphorus, discharges to the mainstem river and as a basis for regulating such discharges. Native species recovery objectives can be reconciled with the requirements of the Clean Water Act by basing waterbody use designation and associated criteria on aquatic life use that recognizes the needs of native species.

The mainstem Missouri River historically carried a large sediment and nutrient load that was important to the evolution and survival of native flora and fauna. These pre-regulation characteristics should be considered in the process of developing water quality standards for the Missouri River.

The federal agencies that are partners in the MRRP, and other major Missouri River ecosystem program and initiatives, should collaborate with ongoing EPA nutrient criteria guidance development process to achieve agreement among themselves and with the states on designated uses for the river, by river segment, to reflect requirements for native species. As a result of this effort, EPA should support states that revise their existing

narrative criteria for the mainstem Missouri River in order to reflect requirements for native species, even if such separate narrative sediment and nutrient criteria later are replaced by numeric criteria. As appropriate, downstream considerations (such as Gulf hypoxia) may be considered in the setting of phosphorus criteria.

There has been a good deal of discussion regarding Corps of Engineers habitat restoration actions along the Missouri River that introduce sediment to the main channel. Specifically, some parties have asserted that private entities are held to a higher standard of permitting and monitoring than a federal agency such as the Corps of Engineers. In order to obtain better, more systematic information on sediment dynamics along the river and specific activities that introduce sediment, it is important that all major activities—whether private sector or governmental—that discharge sediment be similarly monitored and evaluated.

All actions by the Corps of Engineers that discharge sediment to the Missouri River either during project construction or through erosion following construction, should be subjected to monitoring requirements for sediment physical and chemical characteristics. This monitoring should be conducted to ensure that sediment or other pollutants discharged to the river comply with applicable water quality criteria.

1
Introduction

The Missouri River basin extends across portions of ten states in the Midwest and Great Plains—and covers roughly one-sixth of the continental U.S. (Figure 1-1). Up until the mid-twentieth century, the mainstem Missouri River freely migrated back and forth across its wide floodplain. The Missouri was a shallow river and in some areas it assumed a braided pattern with no single, distinct river channel. Before construction of river engineering structures in the twentieth century, the Missouri was well known for its frequent floods, some of them severe. This "unruly river" (Schneiders, 1999) posed flood risks to cities along its course including Omaha, Kansas City, and St. Joseph, Missouri. In rural areas, the river's flooding regime inhibited extensive agricultural use of floodplains.

There was a public desire to moderate these adverse effects of flooding, as well as meet demands for reliable water supplies for irrigation and for cities, hydropower production, and a reliable navigation channel. To satisfy these demands, a network of dams and bank stabilization projects was constructed on the Missouri River mainstem and its tributaries, much of it after World War II, with the intent of controlling and then managing the volumes and patterns of flow of both water and sediment in the river.

Congress authorized most of the mainstem dams on the Missouri River in the Flood Control Act of 1944. The dams were built following the broad outlines of the "Pick-Sloan Plan," a merger of plans for Missouri River basin developed by the U.S. Army Corps of Engineers and the Bureau of Reclamation. The Corps of Engineers constructed mainstem dams to promote flood control, commercial navigation, and other related purposes, while the Bureau of Reclamation was given responsibility for water development along tributary streams and for irrigation. In addition, private entities and the U.S. Department of Agriculture (USDA) built dams of different sizes on the tributaries further affecting water flow and sediment transport. Also, the USDA and the states encouraged private landowners to implement practices that would hold water and sediments on their farms and ranches.

In the 1945 Rivers and Harbors Act, Congress authorized the Missouri River Bank Stabilization and Navigation Project (BSNP). This act completed channelization of most of the Missouri River below Sioux City, Iowa—a process that had begun in the nineteenth century—via a combination of dikes, revetments, and other engineering structures. Today, the dams and bank

FIGURE 1-1 Missouri River Basin, Major Tributary Streams, and Mainstem Dam and Reservoirs. © International Mapping Associates.

stabilization projects are maintained and operated by the Corps, Reclamation, and other entities. Management objectives of the system are hydropower generation, recreation within the pools and in reaches between the structures, reliable municipal and irrigation water supplies, fish and wildlife, and maintenance of a commercial navigation channel. In the process of impounding and channelizing the Missouri River, the Pick-Sloan dams and the BSNP projects have provided numerous economic and social benefits. Implementation of these projects also has had extensive and lasting implications for the river's hydrologic, sedimentary, and ecological systems.

As the Missouri's hydrologic regime became increasingly controlled, the river basin's sediment regime—including the processes of sediment erosion, transport, and deposition—also was changed dramatically. Active migration of the Missouri River channel and the recycling of its floodplain largely ceased, and the Missouri's chutes and sloughs, islands and sandbars, oxbow lakes, and backwater areas went from being dominant, to remnant, features of the landscape. Many of the native species that had adapted to that river and floodplain aquatic and terrestrial habitats in the channels and floodplain were reduced in population, with some listed as threatened and endangered species.

In addition, the historic volumes of sediment formerly transported downstream by the Missouri River were dramatically reduced. At the river's mouth near St. Louis, the pre-regulation Missouri River delivered large amounts of sediment into the Mississippi River that were transported farther downstream and that eventually contributed to deltaic sedimentary processes in coastal Louisiana. Today that sediment supply delivered to the mouth of the river has been reduced to one-third or less of its former volume (Meade and Moody, 2009).

Changes to the river's sediment regime initiated by the mainstem dams and bank stabilization and channelization projects have had a variety of impacts. For example, the river channel immediately downstream of the dams has degraded and lowered because of erosive forces of clear-water releases from the dams. Lowered river bed elevations downstream of the dams in heavily-used recreational areas are a matter of concern for river users. There also are threats associated with lowered river bed elevations, as this may undercut flood protection works, municipal intakes, and bridges across the mainstem river and tributaries (these latter problems are all seen in and near Kansas City, for example). Of particular note is that three native fish and bird species on the Missouri mainstem—the pallid sturgeon, the least tern, and the piping plover—are today listed under the federal Endangered Species Act as threatened or endangered (USFWS, 2000). The declines of these species have been attributed to the river engineering projects that created a colder, deeper, and less turbid river, and to the loss of large areas of sandbar habitat.

The Corps of Engineers has recognized and taken actions to address the adverse consequences of river development on these three species, in compliance with the terms of a Biological Opinion of 2000 (and amended in 2003) issued by the U.S. Fish and Wildlife Service under its Endangered Species Act (ESA) responsibilities (USFWS, 2000, 2003). The expectations of the Biological Opinion have made sediment management a focus of attention since 1989 when consultation began between the U.S. Fish and Wildlife Service (FWS) and the Corps. The Biologic Opinion of 2000 and the 2003 amendment identified alternatives and measures to prevent species extinction and included requirements to construct shallow water habitat to improve conditions for the pallid sturgeon and to build emergent sand bar habitat to benefit the two listed bird species. Habitat creation targets in the 2000/03 Biological Opinion were defined as acres of habitat created by these construction activities.

The Corps' habitat construction activities, however, met with resistance—specifically, in the State of Missouri—where it was argued that discharging sediment into the river as the habitat was being constructed violated the federal and state water pollution control laws (these topics are discussed in greater detail in Chapter 3). It also was argued that adverse effects of such discharges on water quality may be felt not only locally, but also far downstream in the Gulf of Mexico. The Corps argued for the need to restore a portion of the river's sediment regimes and cited the authority of the Biological Opinion. Meanwhile, in this historically sediment-rich river, additional sediment might not only support the recovery of native species, but also reduce the extent of channel bed lowering, and partially restore sediment supply delivered to coastal Louisiana.

Increasing attention to sediment management along the Missouri River and the associated conflicts; demands understanding of river hydraulics and geomorphic processes, relationships between physical responses and habitat quality, and the relationship of sediment management to water quality in a formerly sediment-rich river such as the Missouri. Presently, most direct sediment management responsibilities on the Missouri River mainstem lie with the U.S. Army

Corps of Engineers, under the agency's flood control and navigation authorities, and its responsibilities for habitat loss mitigation.

To provide independent advice on Missouri River sediment and related resource management, in 2008 the Corps of Engineers requested the National Research Council (NRC) Water Science and Technology Board (WSTB) convene an expert committee to address seven sediment-related questions for the Missouri River system. In response to that request the NRC appointed the *Committee on Missouri River Recovery and Associated Sediment Management Issues* (Box 1-1 contains the committee's full statement of task). The breadth of the task statement required this committee to assume a broad and long-term perspective on current sedimentary processes in the Missouri River and how they have changed over time. Discussion and explanation of the sediment regime of the Missouri River, how it has changed over time, and its roles in many river management decisions, are central themes of this report. Those discussions relate to several parts of this report, including the role of sediments in Gulf of Mexico hypoxia (task 2), land building in the Gulf (task 3), Missouri River water quality (task 4), species recovery and bed lowering (task 5), and future management actions (tasks 6 and 7).

This report provides information and recommendations of interest to a broad audience, including several federal agencies—namely, the Corps of Engineers, the U.S. Fish and Wildlife Service, and the U.S. Geological Survey; the U.S. Congress and congressional staff members; Missouri River basin state governments and citizens; nongovernmental organizations, Missouri River communities and citizens, commercial sectors, such as navigation and recreation; and river science and management experts from academia, the private sector, and elsewhere.

BOX 1-1
Committee on Missouri River Recovery and Associated Sediment Management Issues
Statement of Task

1) How and why is sediment a significant variable in the environmental restoration of a river system like the Missouri River?
2) What is the significance of the Missouri River sediments to the Gulf of Mexico Hypoxia problem?
3) What is the significance of the Missouri River sediments to the restoration of Louisiana coastal wetlands?
4) What are the key environmental and economic considerations regarding nutrient loads and/or contaminants in Missouri River sediment? To what extent can such issues be addressed with management strategies?
5) Are there long-term consequences to the lack of sediment in the system to the human environment, either environmentally or economically?
6) Are there alternatives for reintroducing sediment into the system? What are they, and what are the key constraints surrounding these alternatives?
7) Are current Corps' management strategies, restoration tools (e.g., channel widening, creation of chutes, shallow water habitat, etc.) and other activities adequate and comprehensive enough to address issues associated with sediment and nutrients in the system? If not, how might such strategies and activities be improved?

Responses to the questions posed in this report's statement of task about sediment management and nutrient loadings into the river system are not based solely in science or engineering. Rather, they also are grounded within a larger context that includes federal and state water laws and acts, governmental decision-making processes, and the history of settlement and economic development along the river. Therefore, in addition to the science of Missouri River sediment dynamics and ecology, this report discusses, for example, authorizations for Corps of Engineers dam and bank stabilization projects, federal laws (e.g., the Clean Water Act and Endangered Species Act) that relate to sediment management actions, and organizations with decision-making responsibilities for sediment and related resources.

There is considerable overlap among the seven topic areas presented in the statement of task to this committee. It was neither practical nor efficient to arrange the report chapters according to that list. The resulting sequence of chapters addresses those seven tasks, but does not correspond directly to the questions defined in the statement of task.

Chapter 2 addresses topics of Missouri River sediment, the setting and history of the river, and sediment-related processes. It addresses questions 1 and 5—the significance of sediment, and consequences of a lack of sediment.

Chapter 3 discusses the governance structure—laws, authorities, and institutions—for Missouri River management. It provides background on organizations and river management initiatives that are referred to in subsequent chapters and offers advice for improving Missouri River recovery and management actions.

Chapter 4 discusses the consequences for ecosystems and species of various sediment management actions. It addresses question 7—Corps of Engineers Missouri River restoration strategies.

Chapter 5 discusses implications to the river's sediment regimes of various sediment management actions. It addresses questions 3 and 6—sediment management alternatives, and constraints and prospects for improvement.

Chapter 6 discusses Missouri River water quality and sediment. It addresses questions 2 and 4—effects of sediment management on Gulf hypoxia, and the challenges of designing a water quality management system for a river like the Missouri mainstem.

Chapter 7 is a short epilogue that presents some observations regarding science and decision making for Missouri River sediment and related resources.

2
Changes in Missouri River Sediment and Related Processes

The Missouri River drains an area of 530,000 square miles and extends over one-sixth of the conterminous United States. The Missouri River originates at the confluence of the Gallatin, Jefferson, and Madison Rivers near Three Forks, Montana and then flows east and south to its confluence with the Mississippi River just upstream of St. Louis. Along its course, tributary streams such as the Yellowstone, Platte, and Kansas rivers flow into mainstem Missouri River. The basin exhibits a great diversity of landforms and terrain. Because of these differences, sediment loading into the river and its tributaries varies greatly across the basin. Areas in the Rocky Mountains, for example, contribute only a small portion of the river's total sediment load. The Sand Hills of central Nebraska, the Loess Hills of extreme western Iowa and northeastern Nebraska, and other areas of the northern Great Plains supply disproportionately large amounts of sediments to the Missouri River.

Before construction of mainstem dams and extensive river-training structures in the twentieth century, the Missouri River was a major contributor of sediments to the Mississippi River, which transported portions of these sediments downstream and to the Gulf of Mexico. Before 1900, the Missouri-Mississippi River system transported an estimated 400 million metric tons per year of sediment from the interior United States to coastal Louisiana (Meade and Moody, 2009). Approximately 300 million tons were transported by the Missouri River past Hermann, Missouri (Jacobson et al., 2009).

In the mid-twentieth century, six large dams were constructed on the river's mainstem in Montana, North Dakota, and South Dakota. Hundreds of miles of river training structures also were built along the river between Sioux City, Iowa and St. Louis. These structures were authorized by the U.S. Congress and were built to jointly facilitate navigation, control flooding, provide water supplies, and meet other social and economic needs. The large dams were built under the 1944 Pick-Sloan Plan, while many of the bank stabilization and channelization projects were built under the 1945 Bank Stabilization and Navigation Projects (BSNP). These projects, along with changes to land cover and land use across the basin, had substantial influence on the Missouri River's form, dynamics, and sediment regime. Current volumes of sediment transported into Louisiana by the Missouri and Mississippi rivers average roughly 145 million metric tons per year, of which only 55 million tons now pass Hermann, Missouri (Meade and Moody, 2009).

This chapter discusses the importance and the roles of sediment in the Missouri River system. It reviews some fundamentals of sediment erosion, transport, and deposition and how these dynamics affected Missouri River landforms and structure. The chapter also reviews prominent sediment-related changes along the Missouri River during the twentieth century. These changes are strongly linked with changes to river hydrology during the same period, but consistent with this report's statement of task, the emphasis is on sediment and sedimentary processes. The consequences of these major changes in sedimentary processes for ecology, water quality, and infrastructure, also are discussed.

The relevance of sedimentary processes for current and future river management decisions, and the importance of the systematic collection, analysis, and evaluation of sediment data to underpin those decisions, also are examined. In fact, after two to three decades of being underappreciated as compared with Missouri River hydrology and water management, sedimentary processes now are seen as integral to twenty-first century river basin management and merit wider attention and understanding. This chapter also comments on the value of more systematic, comprehensive, and easily accessible sediment data to support future river management decisions and actions.

In addressing these topics, this chapter addresses two questions from this report's 7-point statement of task:

(1) *How and why is sediment a significant variable in the environmental restoration of a river system like the Missouri?* (question 1), and;
(2) *Are there long-term consequences to the lack of sediment in the system to the human environment, either environmentally or economically?* (question 5).

SOURCES OF MISSOURI RIVER SEDIMENTS

The Missouri River has transported large volumes of sediment downstream since at least the last Ice Age, roughly 18,000 years ago. Once the great continental ice sheets had melted and the bulk of their morainal deposits washed downriver, shales and siltstones that lay under portions of the northern Great Plains yielded the largest quantities of fine-grained sediment delivered to the tributary streams of the Missouri River system. A combination of highly erodible soils and low-to-moderate precipitation resulted in large natural yields of fine sediment being delivered to the mainstem Missouri River (Langbein and Schumm, 1958). Meanwhile, the remaining glacio-fluvial materials, plus other coarser sediments derived from tributaries draining areas such as the Sand Hills of Nebraska, formed the several-mile-wide floodplains of the Missouri River. This coarser floodplain sediment was gradually being shifted downvalley through a combination of bank erosion and bar deposition.

The Missouri River historically received eroded sediment from several tributary streams including the Yellowstone, Niobrara, James, Platte, and Kansas rivers. Some of these tributaries drain highly erodible areas (e.g., the Sand Hills) and areas of loess (wind-deposited silt) in northeastern Nebraska and western Iowa. In their travels along the Missouri River in 1804-06, Lewis and Clark were the first to point out that the northern Great Plains, rather than the Rocky

Mountains, are the source areas of large sediment loads to the river (Moody et al., 2003). Other tributaries (e.g., the Yellowstone) drain areas of relatively resistant bedrock and thus have historically been characterized by low turbidities and low sediment yields, supporting species and ecosystems adapted to clear water. This is in contrast to native species, such as the pallid sturgeon, which favored the highly turbid conditions in the mainstem Missouri River and some tributaries. Because different sediment grain sizes function differently throughout a river system, the diversity of these source regions plays an important role in shaping sediment fluxes and dynamics along the length of the Missouri River.

Between the last Ice Age and about A.D. 1950, large quantities of sediment were transported into the Mississippi River and eventually to the Mississippi delta at the Gulf of Mexico. The transport processes were episodic, carrying some sediment particles only short distances each runoff season, storing the particles on the channel bed or in the floodplain during falling-water stages, and re-suspending the stored particles as the river waters rose again during subsequent seasons. More than half of the sedimentary materials that make up the multi-lobed delta that the Mississippi River was deposited on the shores of the Gulf of Mexico during the last 6,000-7,000 years (Blum and Roberts, 2009; Kolb and Van Lopik, 1958; Törnqvist et al., 1996) were “muds”—mainly silt and clay—derived ultimately from the Missouri River basin.

Sediment yields from land encompassed by the Missouri River drainage basin have undergone dramatic and complex changes through settlement and subsequent development. Cropland agriculture was the first of the large human-caused alterations to this millennial-scale pattern of sediment delivery from the Missouri River basin to the Mississippi River and the Gulf of Mexico. This extensive landscape alteration caused greater soil erosion and an increase in river-borne sediment. The most dramatic of these increases in the Missouri River basin were in southwestern Iowa and northwestern Missouri, where the highly erodible soils developed on the extensive loess deposits were exposed to erosion when their soils were plowed (Piest and Spomer, 1968; Piest and Ziemnicki, 1979). The introduction of modern conservation-oriented farming practices reduced the loss of sediment from cultivated fields, and improved grazing management reduced sediment produced from pasture lands. Beginning in the 1930s, the efforts of the U.S. Soil Conservation Service and the effects of the Taylor Grazing Act of 1934 resulted in reduced contributions of upland sediment to the regional rivers (Branson et al., 1981). The geographic pattern of these sediment sources provides a template for understanding what would constitute a relatively natural and beneficial use reference condition when establishing water quality standards for individual reaches of the river and its tributaries (the topic of reference condition is discussed further in Chapter 6).

SEDIMENT EROSION, TRANSPORT, AND DEPOSITION

Characteristics of Sediment Movement

Sediment transported by large rivers includes a variety of sizes, ranging from *clay* (particles less than 4 microns in diameter), to *silt* (4 to 62 micrometers), to *sand* (62 micrometers to 2 millimeters), and *gravel* (2 to 64 millimeters). The rate of travel of sediment, its roles in affecting channel behavior and water quality, and the degree to which sediments and associated particles are exchanged with floodplains, depend on the mode of particle transport. These modes, in turn, depend on sediment grain size and the depth and slope of the river. For example, in rivers like Missouri and Mississippi that experience sharp changes in seasonal water temperature, changes in temperature-modulated viscosity of river water also affect the mode of sediment transport. Coarser particles are transported along or close to the channel bed, while fine particles are carried higher in the water column, which allows fine particles to more frequently enter the floodplain, chutes, and other waterbodies off the main channel. Finer particles are also washed downstream relatively rapidly and dominate the formation and maintenance of coastal wetlands where the Mississippi River sediment load enters the Gulf of Mexico. In contrast, the coarser sedimentary load is more important for shaping channel morphology, including channel bars that are important for native biota, some of them federally threatened or endangered.

Sediment particles on the river bed are referred to as the bed-material load of the river. Transported particles that are finer than those found on the bed are referred to as washload (left side of Figure 2-1). This distinction varies somewhat as discharge changes throughout the year, but since most sediment is transported in floods, this report is concerned primarily with the flows near and above bankfull stage.

Washload (clay, silt, and some fine sand in the case of the Missouri) is so fine that it travels continually suspended in turbulent flow and is rarely deposited within the active streambed, although it may settle out in overbank flow and shallow water habitats at channel margins. The fraction of wash load is the primary determinant of turbidity and of the capacity of the sediment to transport adsorbed chemicals, including phosphate and metals. It is also a large contributor to the formation of floodplain habitats far from the main channel and of coastal deltaic areas. Measured suspended loads (upper right of Figure 2-1) include both washload and larger particles (dominantly sands) that are lifted into suspension from river beds during floods. This latter component is called the suspendible bed-material load (center of Figure 2-1) and it settles from suspension onto the channel bed and bars, or on the floodplain as flow velocities decline. Bedload particles, consisting of coarser sand and some gravel in the case of the Missouri, move along or at least within centimeters of the channel bed by rolling, sliding, and bouncing. Together, the bedload and the suspendible bed-material load constitute the bed material out of which the channel margin and its assorted bars and habitat features are constructed.

The various modes of sediment transport affect its rate of travel, role in affecting channel form and behavior, habitat formation on bars and floodplains, turbidity, chemical transport aspects of water quality, and the degree to which sediment and associated chemicals can be exchanged with the floodplain. In most lowland rivers, the bedload constitutes less than 5 percent of the total sedimentary load. However, bed load is a dominant control on channel morphology, navigability, and bar habitat to a degree that is far beyond its volumetric contribution to the total load. The geography of the river basin, and the engineering activities across the basin, create a supply of sediment with a certain grain size composition. The texture-modulated modes of transport are critical links between sediment supply and its roles in water quality and in habitat formation.

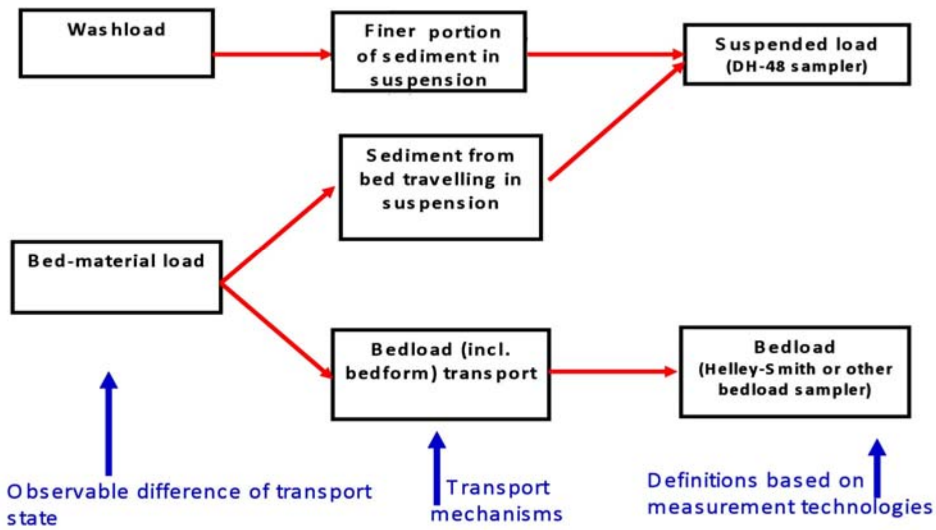

FIGURE 2-1 Grain-size dependent transport mechanisms and their relationships to measured sediment loads.

Chemical and Nutrient Loads

Streams and rivers also transport a variety of natural and human-affected chemical constituents along with sediment. A river's chemical characteristics, as well as sediment grain sizes, are influenced by geology and soils, topography, hydrology, ecosystem processes, climate, and anthropogenic influences. As river systems are dammed, channelized, and otherwise affected by human activities, there typically are changes to the stream's chemical load. Two nutrients of concern in the Missouri and Mississippi River basins today are phosphorus (P) and nitrogen (N). These nutrients are vital for biological growth and are ubiquitous in natural waters and sediment. If other factors, such as light and turbidity, are not limiting, the levels of these nutrients have major effects on aquatic life.

The various chemical forms of phosphorus and nitrogen behave differently in aquatic environments. In particular, nitrogen is more abundant in dissolved forms, whereas phosphorus is largely present in particulate forms (either adsorbed or as a constituent of inorganic and organic particles). Common dissolved forms of nitrogen (such as nitrate) are not particle-reactive; in contrast, dissolved forms of phosphorus (such as phosphate) are particle-reactive and readily adsorbed by sediment. As a result, there is a strong correlation between suspended sediment and total phosphorus concentrations, and changes to the river system that alter the flow of water or sediment in the system are likely to cause a larger change in the concentration and transport of phosphorus than of nitrogen (Wetzel, 2001).

The delivery of large volumes of nutrients from the Mississippi River Basin to the Gulf of Mexico, and associated hypoxia in deeper waters of the Gulf, is a prominent national water quality concern. Analyses of river flows and concentrations have been used to estimate of loads of phosphorus and nitrogen from each of the major tributaries of the Mississippi River (Alexander et al., 2008; USEPA, 2007). Based on what is commonly understood about the sediment-association of phosphorus, current and future projects for sediment regime restoration in the Missouri River may increase phosphorus supply to the Mississippi. From a broader historical perspective, as the Missouri River always has carried a tremendous sediment load, and natural suspended sediments carry a certain amount of phosphorus, the pre-anthropogenic river thus likely carried significant phosphorus loads into the Mississippi River. However, it is not known what portion of these phosphorus loads reached the Gulf were trapped in coastal wetlands, or were captured further upstream in the system.

Roles of Sediment in Large River Systems

The Missouri River's native fish and bird species evolved in environments with high turbidity, large volumes of mobile sediment, and hydro-geomorphic conditions consistent with a sediment-rich river. In contrast, many other rivers and streams nationwide, including some Missouri River tributaries, naturally contain far lower concentrations of sediment. The sediment management challenges posed by varying concentrations of sediment across a river basin were noted in a Geological Society of America compilation of papers on river system management and human impacts:

> To many environmental scientists—such as those concerned with total maximum daily loads (TMDLs)—all sediment is treated as a pollutant. This perspective is in conflict with the need to introduce sediment to sediment-starved reaches below impoundments or where coarse sediment needs to be recruited to replenish spawning gravels on riffles and bars (James et al., 2009).

On so-called "clear-water" streams and rivers, excess inputs of sediment—for example from basin land uses such as agriculture or localized activities such as construction—can raise sediment concentrations in the water far higher than natural background or historical levels. In these cases, sediment rightly can be viewed as a pollutant, with potentially severe impacts on species native to that tributary, to aesthetics, and to river form and water quality. In the Missouri River basin, however—in which pre-anthropogenic concentrations of sediment in reaches of the mainstem and some tributary streams were greater than those found in the river today—the designation of sediment as a "pollutant" is fraught with ambiguity (Chapter 6 contains further discussion of this topic).

HYDROLOGIC AND GEOMORPHIC CHANGES TO THE MISSOURI RIVER

Over long reaches of the Missouri River, hydrodynamic and geomorphic processes have changed considerably over the past century. Dams, levees, dikes, and revetments have been constructed and now are operated to facilitate services such as: transportation of bulk commodities through commercial navigation, flood protection for farms and cities, reliable water supply, hydropower generation, and water-related recreation. This section describes key historical changes to the Missouri River, with an emphasis on changes to or relevance of sedimentary processes for the pre-regulation Missouri River, the post-regulation Missouri River, and changes to Missouri River ecology.

The Pre-Regulation Missouri River

Early accounts of the Missouri River date back to Lewis and Clark and the expedition of their Corps of Discovery in 1804-1806, in which they made numerous entries in their journals about hydrology, turbidity, and river morphology. As the Great Plains were subsequently explored and settled, many observations and written accounts helped to produce an early picture of the river's morphology and character.[1]

The pre-regulation Missouri River assumed different morphologies in different reaches of the river. In many stretches, the pre-regulation Missouri River was a multi-channel system, with a primary channel and often multiple secondary channels (called 'chutes' on the Missouri River), widespread bars, islands, and shallow sloughs (Hallberg et al., 1979; Moody et al., 2003). The river also featured natural levees, backwater lakes, large meander loops, oxbow lakes, and sandbars and dunes (Figure 2-2). Width of the main river channel was highly variable, ranging

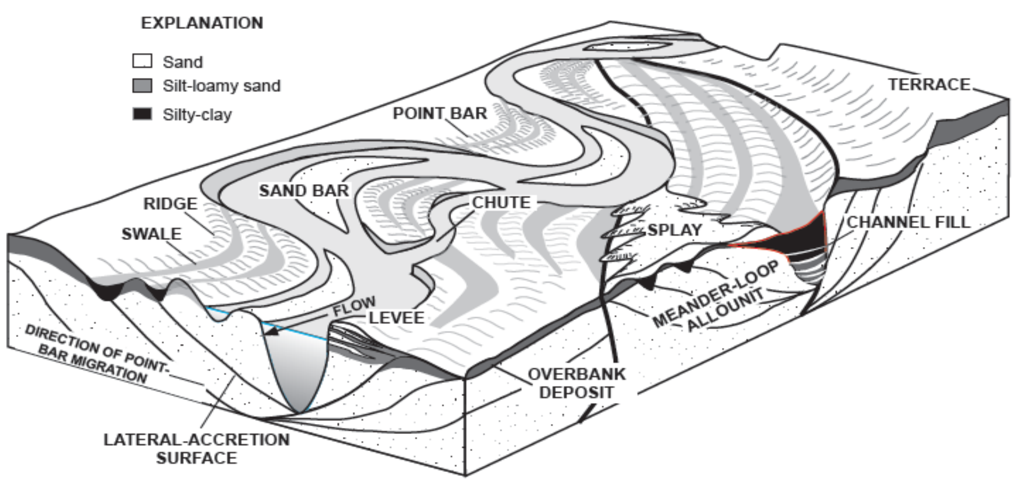

FIGURE 2-2 Idealized cross-section of a large river-floodplain ecosystem. Before extensive twentieth century regulation, the Missouri River resembled this diagram in some reaches. In other reaches, the Missouri did not have a single, distinct river channel and assumed a more braided, multi-tributary character. SOURCE: Jacobson, et al., 2007.

[1] For more information on these topics, the interested reader is encouraged to consult Ambrose, 1997; Ferrell, 1993; NRC, 2002; and Schneiders, 1999.

from roughly 1,000 to 10,000 feet during normal flow periods to 25,000-35,000 feet during floods (Schneiders, 1999). In some areas during large floods, the river flowed bluff-to-bluff and covered a width up to 17 miles (see NRC, 2002 for additional description of the pre-regulation Missouri River). Early accounts also described near-ubiquitous woody debris, or "snags" in the channel, present at all times and mobile during floods (Figure 2-3). These snags derived primarily from riverbank erosion, a process that moved trees and other organic material from the floodplain surface into the channel. Vegetation along the Missouri River corridor was dense, with sandy low-water flats along the channel margin, stabilized by thickets of young willows and cottonwood, and large forest trees on islands and the floodplain (Johnson, 1992; Schneiders, 1999).

The processes of river bank erosion and lateral migration of the river channel were prominent in the pre-regulation Missouri River. In areas where the pre-regulation Missouri River channels migrated back and forth across the floodplain, river banks and sediment were eroded on the outside banks of mobile bends, while sediments were deposited on the bends' inside edges, or on mid-channel bars where young vegetation slows flow and scavanges sediment (Johnson, 2000). These processes played important ecological roles in the pre-regulation Missouri (Johnson et al., 1976; Johnson, 1992). The overall sediment regime was one of intermittent transport, with some sediments stored for decades or centuries in bars or the floodplain, then remobilized by a flood event (NRC, 2002; Slizeski et al., 1982). As a channel's location changed through the processes of erosion and sedimentation, diversity developed in the riparian vegetation as distance from the present channel increased (Figure 2-4). Channel migration eroded older, well-established vegetation on the outside of river curves, while new bars on the inside of river curves were suitable for pioneer vegetation communities such as cottonwood and willow. Channel migration also contributed to floodplain species biodiversity by creating a mix of landforms such as oxbow lakes, sloughs, and backwater swamps with differing soil textures, chemistry, and inundation regimes.

Distribution of riparian vegetation was also heterogeneous because tree species differ in their tolerances to flooding, sedimentation, and physical damage from floodwaters and debris (Hupp, 1988). Channel widening and lateral migration removed both living and dead trees from eroding banks, and many of these collected in the channel after floodwaters receded. This large woody debris (i.e., "snags") contributed submerged substrate for invertebrates that are consumed by fishes and other vertebrates. Woody debris also provided cover for fish and contributed hydraulic roughness to the riverbed that locally modified channel bed texture, bathymetry, water depth, and organic matter distribution (Gurnell et al., 2002; Sedell and Froggatt, 1984).

Riparian vegetation stabilized riverbanks and sandbars and slowed bank erosion and channel migration rates (Gran and Paola, 2001; McKenny et al., 1995). The presence of vegetation exerted a strong physical presence on floodplains by increasing surface roughness, reducing flow velocity, and capturing sediment from flood waters. Early-successional trees established on low sandbars near mean river level trapped and immobilized as much as 5-6 meters of sediment (Johnson et al., 1976; Scott et al., 1997). The river's sand bars and associated biotic communities are important habitat for many native riparian species whose life cycles and populations depended on the existence of the bars, as well as their continuing movement. Occasional shifting and movement of sand bars and other riparian landforms made long-term

FIGURE 2-3. Numerous “snags” characteristic of the pre-regulation Missouri River.
SOURCE: Reprinted, with permission, from Joslyn Art Museum. Watercolor and pencil drawing by Karl Bodmer, made on 26 April, 1833, on the Missouri River near the mouth of the Nemaha River. (Original in Joslyn Art Museum, Omaha, NE; image here from Moody et al., 2003).

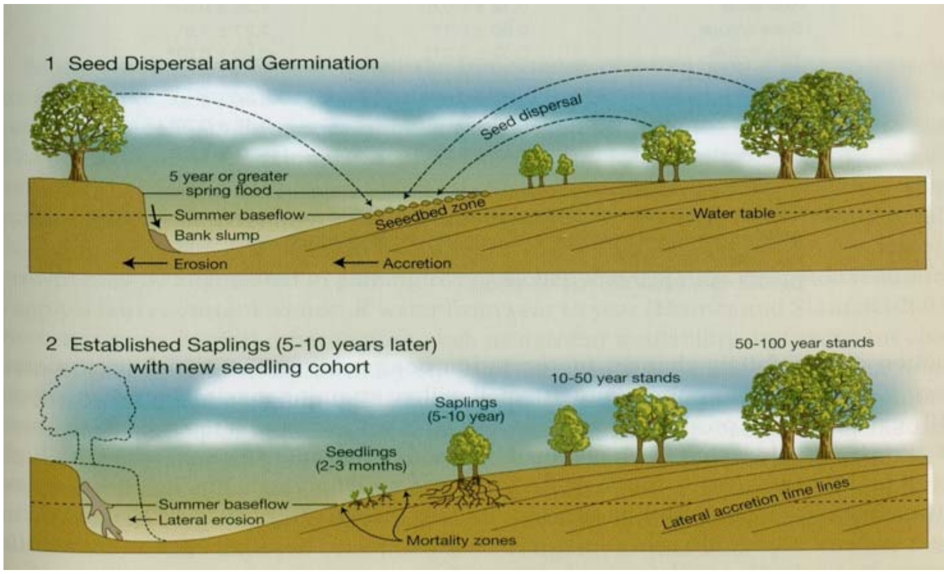

FIGURE 2-4 Model of lateral channel movement; accumulation of sediment on the inside (right side, above) of a channel bend; and seed dispersal, germination, and establishment.
SOURCE: Reprinted, with permission, from Braatne et al., 1996. © 1996 by NRC Research Press.

colonization by vegetation difficult, and the absence of vegetation made it difficult for predators to prey upon the nests of sandbar nesting birds (Johnson, 2000; Osterkamp and Hedman, 1982).

Floods were common and widespread on the pre-regulation Missouri River and played important hydrologic and ecological roles. Floods allowed for the redistribution of sediment between the river's main channel and its floodplains. As Missouri River flows increased during the spring, the river would erode sediment from its bed and its banks. Overbank flows allowed the main channel to connect to backwater areas, allowing for free exchange of sediment and biota. As discussed above, scouring of the river banks during floods washed trees and other vegetation into the river and redistributed snags already in the channel. Floods also replenished groundwater, a process important for sustaining the growth of floodplain vegetation. As floods receded and water volumes and velocities decreased, the degraded channel would rapidly refill with sediment; secondary channels and meanders would become isolated from the main channel; and fresh substrate material would be deposited for subsequent colonization by plants and animals (also see NRC, 2002). The shifting of the Missouri River's channel with abundant bank erosion and sediment accretion during floods was legendary (Johnson et al., 1976; Schmulbach et al., 1992). For example, Duncanson (1909) reported the erosion of approximately 30 acres of Missouri River floodplain on a single bend during a 24-hour period. Channel changes were especially dramatic when tight bends (channel necks) were "cut off" and formed oxbow lakes (Weaver, 1960; Shields, 2000).

The Post-Regulation Missouri River

Many river regulation activities took place on the Missouri River before 1945. For example, dredging, clearing of forests to provide fuel for steamboats, snag removal, and early channelization efforts date back to the nineteenth century. Nevertheless, the most significant changes to river hydrology and sedimentary processes were realized under the Pick-Sloan Plan of 1944 and the Missouri River Bank Stabilization and Navigation Project of 1945[2]. These legislative actions clearly are major landmarks in the river's environmental history.

Bank and Channel Stabilization

The federal Missouri River Bank Stabilization and Navigation Project (BSNP) created an inland waterway transportation system, as well as providing protection for utilities, transportation networks, bridges, and adjacent landowners and farms by preventing river channel migration and reducing the potential for over-bank flooding. The project area extends 735 river miles from Sioux City, Iowa, to the mouth of the Missouri River near St. Louis, Missouri. This project replaced an ever-changing riparian landscape with a fixed navigation channel and stable floodplain lands along both shores. Missouri River bank stabilization and river control projects

[2] The Pick-Sloan Plan was part of the 1944 Flood Control Act, while the Missouri River BSNP was part of the 1945 Rivers and Harbors Act.

were authorized under Rivers and Harbors Acts of 1912, 1917, 1925, 1930, 1935, and 1945 (USGS, 1998). The project was officially completed in 1981 (ibid.).

The principal mechanism for providing minimum navigation depths on the Missouri River involved channel constriction. Beginning in the late nineteenth century, the navigable portion of the Missouri River channel was narrowed to as little as one-half to one-third of its original width (Funk and Robinson, 1974; Hallberg et al., 1981; Pinter and Heine, 2005) primarily through the emplacement of "wing dikes," structures built perpendicular to the bankline to trap sediment, stabilize river banks, and produce a single channel (Figure 2-5). Engineering structures built under the BSNP immobilized sediment that formerly was transported downstream and, in so doing, narrowed the channel. Land accreted along the lower Missouri River, downriver of Sioux City:

> …. from 1910 to 1981, yielding an average deposition rate over these 71 years of approximately 45.5 x 10^6Mg/y, equivalent to about 14 percent of the pre-dam (1948-1952) annual suspended-sediment load at Hermann, Missouri. Land accretion activity was more concentrated from the early 1930s to mid 1960s, so deposition rates may have been as high as 107 x 10^6 Mg/y, equivalent to almost one-third of the pre-dam annual suspended-sediment load at Hermann. …. Accreted land preferentially sequestered coarse sediment sizes from the total suspended load whereas finer sediments were washed downstream
> (Jacobson et al., 2009).

Bank-protection works slowed the lateral shifting of the river and the associated bank erosion of sediment, derived originally from the uplands, which previously contributed to or maintained the sediment load of the river.

Channelization of the Missouri has conferred social and economic benefits through support of commercial navigation (GAO, 2009). Adjacent lands behind revetments and levees provided areas favorable for agricultural production and sites for river communities and infrastructure. However, the narrow, controlled river channel significantly reduced habitat that was formerly provided from the pre-regulation channel and migration processes and that was important to the natural riverine system (Hesse, 1987, 1993; NRC, 2002). It also caused lowering of the bed and consequent (and expensive) damage to infrastructure such as levees, water intakes, and transportation structures extensively along the Missouri River mainstem and the lower reaches of its tributaries (Jacobson and Galat, 2008; Schmulbach, et al., 1992).

Mainstem Dams and Reservoirs

Construction of the Missouri River mainstem dams spanned several decades and coincided in part with channelization of the lower river. Fort Peck Dam, constructed in the 1930s under the National Industrial Recovery Act, was the only large Missouri River dam not part of the Pick-Sloan Plan. Construction of Fort Peck Dam stimulated channelization work on the lower Missouri during that period. The dam was closed in 1937, and construction was

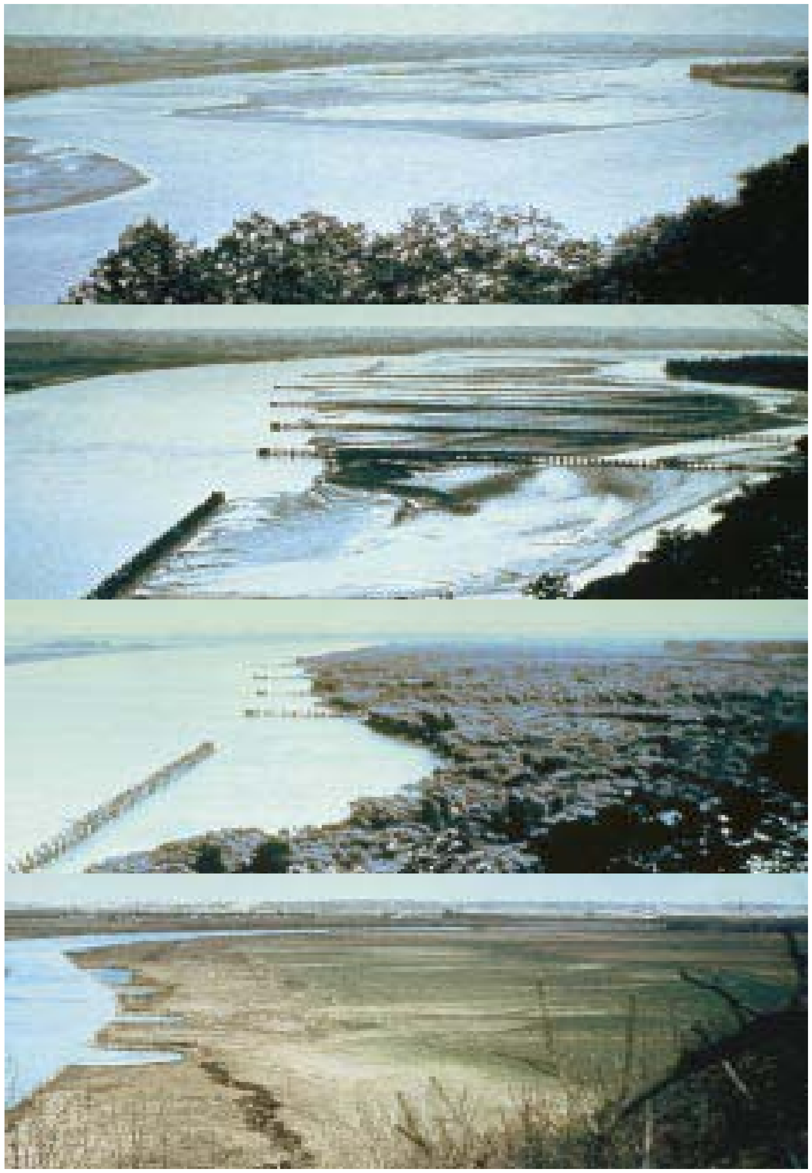

FIGURE 2-5 Photographs taken at Indian Cave Bend on the Missouri River near river mile 517, about 18 miles upstream from Rulo, Nebraska. They illustrate the river before (1934; top photo) and after (1935, 1946, and 1977) the construction of brush dikes that narrowed and channelized the river. View is looking downstream from Nebraska (near bank) into Missouri (far bank). These photos illustrate substantial alteration of riparian and in-channel habitats.
SOURCE: USGS, 1998.

completed in 1940. Authorized purposes of Fort Peck Dam included flood control, irrigation, navigation, and power generation.

The five other large Missouri River mainstem dams were authorized under the Flood Control Act of 1944, which represented a fusion of the plans of Col. Lewis A. Pick of the U.S. Army Corps of Engineers and those of William G. Sloan of the Bureau of Reclamation. Construction began first on Fort Randall and Garrison dams in 1946 (see Table 2-1). Oahe Dam followed in 1948, Gavins Point Dam in 1952, and construction commenced on Big Bend Dam in 1959. Each structure required several years for construction and, following closure, time before each reservoir was filled to capacity.

Closure of the Mainstem Dams and Impacts on Sediment Processes

During the mid-twentieth century, this region-wide conveyor of sediment was converted to a series of impoundments that included some of the largest storage reservoirs in North America (notably Lake Oahe and Lake Sakakawea; see Figure 1-1). This transformation resulted in decreased volumes of transported sediment, sediment deposition in the mainstem reservoirs, and caused channel bed and bank erosion downstream of each dam. Farther downstream, delivery of sediment from the Missouri into the Mississippi River system was reduced greatly following the closure of the Missouri River mainstem dams.

TABLE 2-1 Missouri River Mainstem Dams and Reservoirs

Dam	Location (river mile)[3]	Reservoir	Began	closed	completed	storage (acre-feet)
Fort Peck Dam	1767	Fort Peck Lake	1933	1937	1940	18,700,000
Garrison Dam	1387	Lake Sakakawea	1946	1953	1954	23,000,000
Oahe Dam	1071	Lake Oahe	1948	1958	1962	23,500,000
Big Bend Dam	987	Lake Sharpe	1959	1963	1966	1,900,000
Fort Randall Dam	878	Lake Francis Case	1946	1952	1953	5,500,000
Gavins Point Dam	811	Lewis and Clark Lake	1952	1955	1957	492,000

SOURCES: Data from Branyan, 1974; Pinter and Heine, 2004.

[3] Distance from Missouri-Mississippi confluence.

The closure of the two farthest downstream dams on the Missouri River—first Fort Randall Dam (South Dakota) in 1953 and later Gavins Point Dam (Nebraska-South Dakota border; see Figure 1-1) farther downriver in 1955—contributed to sharp reductions in suspended-sediment discharges. Suspended-sediment discharge at Yankton, South Dakota, decreased from 160 million tons per year in 1952 to 50 million tons per year in 1953 following the closure of Fort Randall Dam (Figure 2-6). This was followed by a smaller reduction to about 10 million tons per year during the two years before the closure of Gavins Point Dam in 1955 just upriver from Yankton. Since closure of Gavins Point Dam, sediment discharge at Yankton has declined further to 0.25 million tons per year (Jacobson et al., 2009). The closing of the two dams thus resulted in a decrease in suspended-sediment discharge at Yankton of about 160 million tons per year. Similar effects were recorded in sediment records all along the Missouri and downstream on the Mississippi River (Meade and Moody, 2009; Figure 2-6).

While the mainstem Missouri dams were being completed, many dams and reservoirs were being built on the tributaries. For example, twelve reservoirs were constructed across the Kansas River basin from 1952-69, with six of those reservoirs having water-storage capacities larger than Lewis and Clark Lake behind Gavins Point Dam on the Missouri mainstem (Perry, 1994). Pre-dam discharges of suspended sediment from the Kansas River (based on only a few years of record: 1929-30, 1949-50) averaged 30-40 million metric tons per year (Secretary of War, 1935; USACE, 1957). During the record flood year of 1951, the Kansas River carried 150 million metric tons of sediment into the Missouri River. Following dam construction (data available for 1964-73), however, annual sediment loads of the Kansas River averaged just 10-12 million metric tons (USACE, 1970, 1972, 1976).

The mainstem Missouri River dams presently store about 3.7 million acre-feet (or approximately 6 trillion tons) of sediment (Table 2-2). These materials reduce the storage capacity of these six mainstem reservoirs. The greatest loss of storage in terms of percentage reduction is Lewis and Clark Lake behind Gavins Point Dam, where reservoir storage loss due to sedimentation is more than 20 percent of total storage.

Channel Incision Downstream of Dams

Decreased sediment loads during the second half of the twentieth century were accompanied by rapid channel incision downstream of the dams (Livesey, 1965; Sayre and Kennedy, 1978; Holly and Karim, 1986). Sediment-poor, or "hungry," water released from reservoirs caused substantial channel incision and bed degradation. Degradation was greatest, reaching 9 feet or more, just downstream of Gavins Point dam, with values near 1.3 feet being recorded near Omaha at the confluence with the Platte River (Heine and Lant, 2009). Farther downstream, areas of minor aggradation and degradation alternate all the way to the Mississippi confluence. Downcutting was accompanied by severe bank erosion, channel widening, and landsliding along steepened bluffs (Rahn, 1977). In addition to incision on the mainstem Missouri, downcutting also propagated up many of the Missouri River tributaries, with similar effects to those noted along the Missouri itself (Heine and Lant, 2009). Incision has lowered water tables on adjacent floodplains, thereby draining natural floodplain lakes and reducing tree

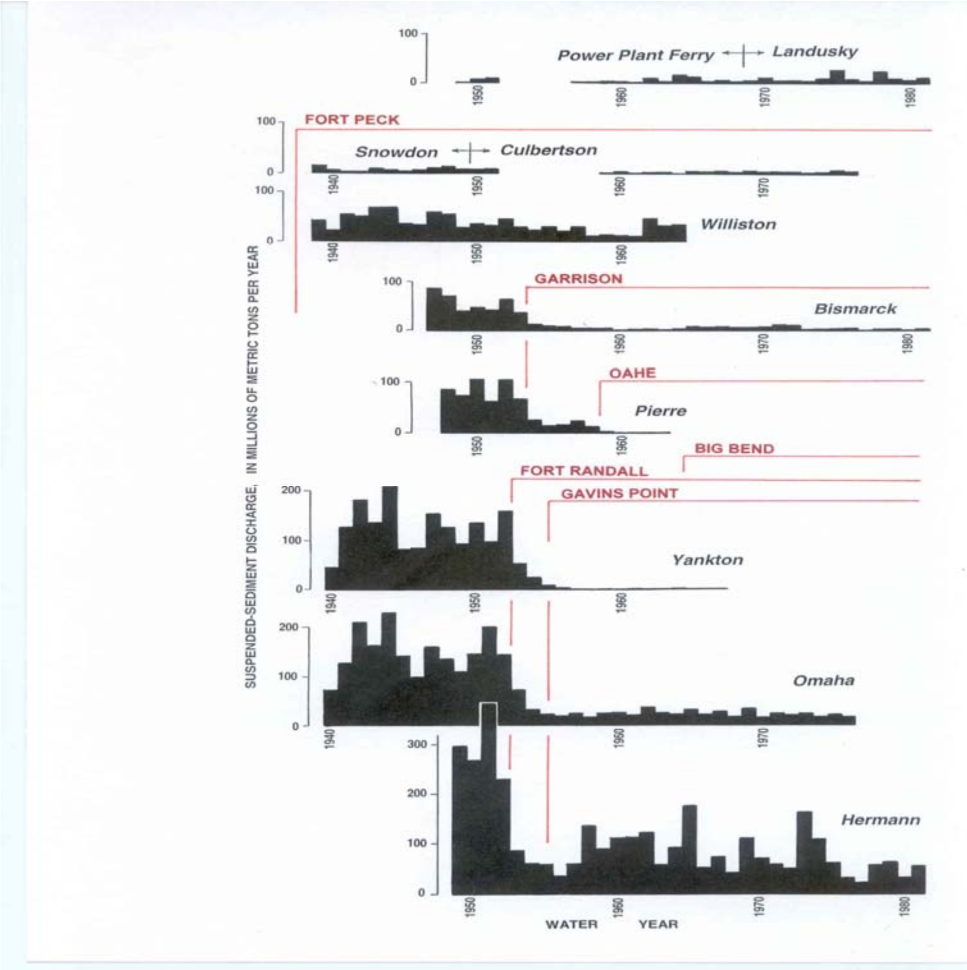

FIGURE 2-6 Annual suspended-sediment discharges from select Missouri River sites in the years before, during, and after the closures of the major mainstem dams. Red lines show the relative locations (horizontal) and closure dates (vertical) of the six major dams.
SOURCES: Sediment data through 1974 from Corps of Engineers (USACE, 1951, 1957, 1965, 1970, 1972, 1976).
Post-1974 data from published USGS records (Landusky, Culbertson, and Bismarck stations) and unpublished data of Corps of Engineers (Alvin Coop, Kansas City District, personal communication to R.H. Meade, 1982).

TABLE 2-2 Missouri River Mainstem Dam Sediment Storage and Capacity

Reservoir	Year (survey)	Total Storage below Exclusive Flood Control	Total Storage Loss (acre-feet)	Total Storage Loss (%)	Annual Loss (%)	Expected Life (years)
Fort Peck	2007	18,463,000	1,094,000	5.6	0.08	1030
Garrison	1988	23,821,000	907,000	3.7	0.11	920
Oahe	1989	23,137,000	614,000	2.6	0.08	1170
Big Bend	1997	1,799,000	181,000	9.1	0.27	340
Fort Randall	1996	5,418,000	790,000	12.7	0.30	290
Gavins Point	2007	450,000	125,000	21.7	0.42	190

SOURCES: Data from Boyd et al., 2009; Jacobson et al., 2009; Stark and Pridal, 2009.

growth (Reily and Johnson, 1982). It also has reduced channel migration rates and increased average depths within the channel. Incision generally attenuates with distance from the dam, but it is still detectable at Sioux City, Iowa (roughly 60 miles downstream of Gavins Point Dam), and increases again markedly in the vicinity of Kansas City, Missouri. By contrast, in the upper reaches of reservoirs, sediments are deposited where rivers enter the slack water of reservoirs. These are zones of deposition, where the river builds deltas that progressively extend into the reservoirs.

Decreased Sediment Delivery to the Gulf Coast

Closure of the Missouri River dams and the bank stabilization project coincided historically with a net reduction by half in sediment delivered to the Gulf of Mexico (Keown et al., 1986; Meade and Parker, 1985). A recent publication on Mississippi and Missouri River sediment transport volumes, and how they have changed over time, stated:

> Before 1900, the Missouri–Mississippi River system transported an estimated 400 million metric tons per year of sediment from the interior of the United States to coastal Louisiana. During the last two decades (1987–2006), this transport has averaged 145 million metric tons per year (Meade and Moody, 2009).

Figure 2-7 shows the historical predominance of sediments from the Missouri River to the Mississippi River and downstream to Louisiana. Figure 2-8 further illustrates a sharp decline in sediment volumes transported by the Missouri River after construction of dams and bank stabilization projects in the 1940s, 1950s, and 1960s.

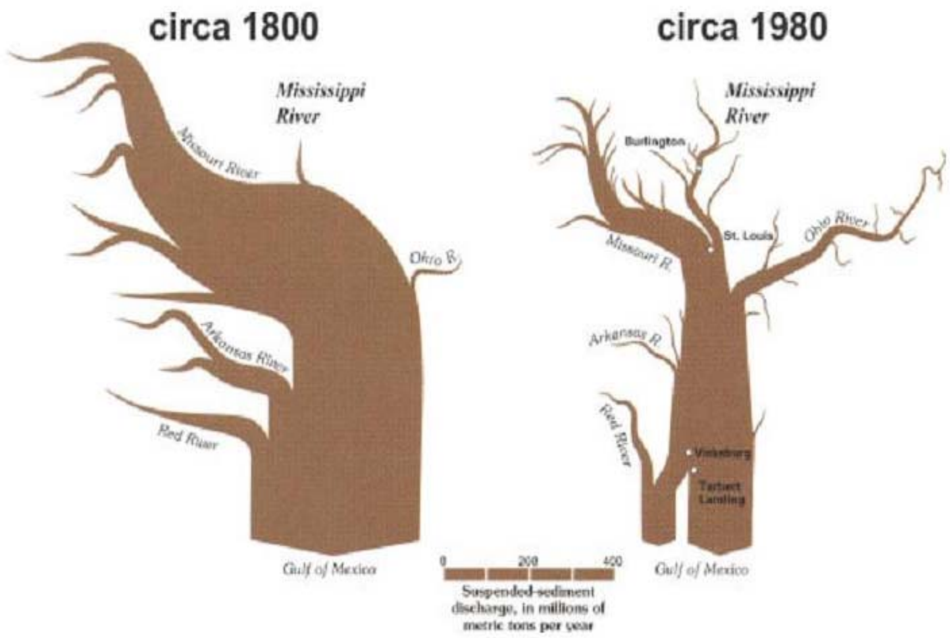

FIGURE 2-7 Schematic diagrams of average annual suspended-sediment discharges in Missouri–Mississippi River basin.
SOURCE: Reprinted, with permission from Meade and Moody, 2009[4]. © 2009 by John Wiley & Sons, Inc.

In addition to directly trapping sediment, the larger storage dams reduced peak flows that further reduced the river's ability to transport large volumes of sediment. Meander cutoffs and the construction of river-training structures on the Missouri and lower Mississippi rivers also have immobilized large amounts of sediment throughout the basin and along the Missouri and Mississippi mainstem (Meade and Moody, 2009).

[4] From Meade and Moody, 2009: "Diagrams were originally published by Meade (1995). Diagram for 1800 is an impressionistic estimate, based on our readings of the Journals of Lewis and Clark (Moody *et al*., 2003), results of Humphreys and Abbot (1876), observations reported by Mark Twain (1883) and on more recent analyses (Blevins, 2006) that concluded sediment concentrations in the Missouri River have decreased at least 70–80% from predevelopment conditions." The diagram for 1980 was "compiled mostly from data of Keown et al. (1981, 1986) plus supplemental data on lower Missouri River from Parker (1988) and data on lower Ohio River from Moody and Meade (1992, 1993, 1995)."

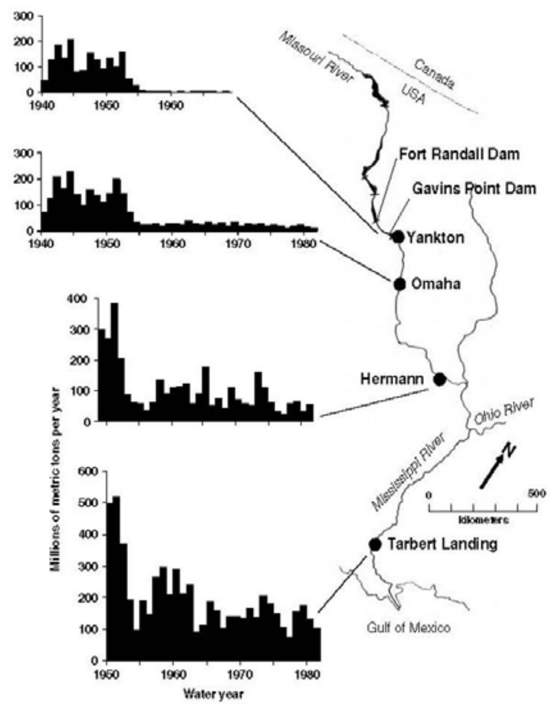

FIGURE 2-8 Suspended-sediment discharges at stations on Missouri River at Yankton, South Dakota; Omaha, Nebraska and Hermann, Missouri; and on the Mississippi River at Tarbert Landing, Mississippi, 1940–1981. Principal effects on records at Yankton and Omaha, and probably on records at Hermann, were due to the closures of dams at Fort Randall (1953) and Gavins Point (1955).
SOURCE: Reprinted, with permission from Meade and Moody, 2009[5]. © 2009 by John Wiley & Sons, Inc.

Current Sediment Dynamics on the Lower Missouri River

An extensive and thorough assessment of current data and analyses for developing a sediment budget for the lower Missouri River is presented in a paper jointly authored by U.S. Geological Survey and Corps of Engineers scientists (Jacobson et al., 2009). As its authors explain:

[5] From Meade and Moody, 2009: "Diagrams were originally published by Meade (1995). Diagram for 1800 is an impressionistic estimate, based on our readings of the Journals of Lewis and Clark (Moody *et al*., 2003), results of Humphreys and Abbot (1876), observations reported by Mark Twain (1883) and on more recent analyses (Blevins, 2006) that concluded sediment concentrations in the Missouri River have decreased at least 70–80% from predevelopment conditions." The diagram for 1980 was "compiled mostly from data of Keown et al. (1981, 1986) plus supplemental data on lower Missouri River from Parker (1988) and data on lower Ohio River from Moody and Meade (1992, 1993, 1995)."

> Sediment budgets—an accounting of sediment transport, erosion, and deposition—are fundamental to understanding geomorphic evolution of altered river systems. In a dammed river system, the sediment budget quantifies the flux of materials available for maintaining or creating habitat, therefore strongly constraining the potential for management or restoration (Jacobson et al., 2009).

All numbers and data in the following section on current sediment dynamics in the Missouri River draw from this 2009 paper unless noted otherwise.

The pre-dam (1940-1952) sediment flux past Yankton, South Dakota in the vicinity of Gavins Point Dam was about 125 million tons per year[6]. Sediment transport past Hermann, Missouri was about 300 (298-326) million tons per year. The difference between these two stations indicates that about 175 million tons per year was supplied to the Missouri River mainly by large right-bank tributaries such as the Platte and Kansas rivers and, to a lesser extent, by left-bank tributaries (such as the Nishnabotna River) draining loess lands.

Since this period also witnessed continuing engineering projects to sequester sediment within the floodplain and stabilize the channel, tributary streams must have been supplying more than 175 million tons per year, but the amount is unknown without further analysis of volumetric changes in floodplain storage. However, by 1980 when the main period of sediment sequestration was declining, the total amount of sediment stored within the floodplain behind groynes and levees as a result of engineering projects dating back to the early part of the twentieth century was approximately 3.2 gigatons. This volume implies an average accumulation rate of about 45 million tons per year, averaged throughout the 1910-1981 period, or more representatively a rate of about 100 Mt/yr averaged throughout 1930-1960, the period of most intensive engineering activity. On the basis of samples excavated from trenches on the floodplain, the grain-size composition of this stored sediment has been estimated to be 78 percent sand and 22 percent silt-clay (Jacobson et al., 2009).

Given that Lewis and Clark Lake behind Gavins Point Dam captures all free sediment from upstream dams, the post-impoundment Missouri carries essentially no load (0.25 Mt/yr) at Yankton, SD and then begins to recruit sediment from its bed and tributaries so that the load increases to 7.3 Mt/yr by Sioux City, Iowa and 58 Mt/yr (~25 percent sand) at Hermann, Missouri. Recruitment of sediment from the bed has resulted in degradation of the average bed elevation by about 10 feet at Yankton, diminishing downstream to approximately zero in the Omaha-Nebraska City reach. Despite additions of sediment from the tributaries, the bed elevation is reduced also by about 2 to 8 feet due to commercial sand dredging in the vicinity of Kansas City. Loads generally have decreased since dam closure, or at least since the 1993 flood, especially beyond Nebraska City downstream of the Platte confluence. Reasons for this decline are probably some combination of gradual stabilization of the degraded channel, intensified flushing of the sediment from the river by the 1993 flood, commercial sand dredging, and especially reduction of sediment eroded from the tributary watersheds as a result of land management (dredged sand amounts to approximately 40 percent of the sand load at Hermann).

[6] Moody and Meade (2009) estimated 160 million tons per year for the same period, indicating uncertainties that are irreducible at this point.

CHANGES TO MISSOURI RIVER ECOLOGY

Effects on Missouri River Fishes

Changes in Missouri River hydrology, and the dynamics and volumes of sediment transport, during the twentieth century have had far-reaching effects on river ecology and its pre-regulation assemblage of biota. The Missouri River's native fish species evolved in environments with high turbidity, swift current, a scarcity of quiet backwaters, and an unstable sand-silt bottom (Pflieger, 1971)—habitat conditions that were altered and diminished substantially during the twentieth century. As a result of marked habitat changes, there have been many effects on the river's native fishes.

The term "big river" fish was coined to describe the distinctive assemblage of fishes inhabiting the Missouri-Mississippi system (Pflieger, 1971). Within the Missouri River, species that are predominately benthic specialists reside and exhibit a diversity of ecomorphological adaptations for high turbidity (Galat et al., 2005). These adaptations include reduced eyes, external taste buds and olfactory receptors on dorsal and pectoral fins, and an array of well-developed electrosensory organs and chemosensory organs to navigate, locate food, and avoid predation in a low visibility environment. The environmental factors that influenced the anatomy of Missouri River's fishes are similar to those operating in other largely turbid, dryland rivers like the Colorado (Mueller et al., 2005) and the Rio Grande (Calamusso et al., 2005).

As sediment concentrations have declined in the Missouri, there has been a corresponding decline of fishes that historically occupied highly turbid main-channel habitats and their replacement by visually feeding species that are competitively superior in less-turbid waters (Bonner and Wilde, 2002; Cross and Moss, 1987; Pflieger and Grace, 1987). Decreases in specialized native big river fishes have been attributed to reductions in suspended sediment and turbidity in the lower Missouri River, including the now federally listed as endangered pallid sturgeon, and imperiled paddlefish, blue sucker, and flathead chub (Pflieger and Grace, 1987). More recently, 11 of the Missouri's 73 big river fishes were identified by two or more mainstem states as imperiled due to a combination of factors including impoundment, changes in flow and temperature regimes, reductions in channel habitat complexity, reduced turbidity, and introduced fishes (Galat et al., 2005). Corresponding increases in abundance have occurred in sight-feeding carnivorous fishes that feed on open-water zooplankton in clear water. In many reaches of the river today, non-native sport fishes are in greater abundance than native species. These nonnative species often are more tolerant of altered conditions of temperature, turbidity, and habitat (NRC, 2002).

Much of the attention on Missouri River native fish species today revolves around one species: the pallid sturgeon (*Scaphirhynchus albus*). The pallid sturgeon was listed as endangered throughout its entire range in September, 1990. Some scientists consider the species as being close to extinction (Dryer and Sandvol, 1993). Pallid sturgeon inhabited and utilized the floodplains, backwaters, sloughs, and main channel pools and snags in the pre-regulation Missouri River. Some scientists have expressed concern that the pallid sturgeon cannot reproduce in the Missouri River's post-regulation channelized and reservoir habitats (Henry and Ruelle, 1992; Ruelle and Henry, 1994). The Corps of Engineers and the U.S. Fish and Wildlife

Service today are implementing actions along the Missouri River, downstream of Gavins Point Dam in South Dakota, Nebraska, Iowa, and Missouri, designed to improve habitat conditions for the pallid sturgeon (Chapter 4 provides details on the Corps' ongoing Missouri River emergent sandbar habitat and shallow water habitat projects). These actions are being taken in accord with a 2000 federal Biological Opinion, and amended in 2003, to avoid jeopardizing the continued existence of the pallid sturgeon (Chapter 3 provides details of the Fish and Wildlife Service Biological Opinion).

Effects on Missouri River Birds

Hundreds of native species of birds use the Missouri River ecosystem for nesting. Many of them occupy the successionally diverse forests on the floodplain and riverine islands. Two bird species, the least tern (*Sterna antillarum)* and the piping plover (*Charadrius melodus*), are federally listed as endangered. Both these birds nest in shallow, inconspicuous depressions in sandy or gravelly patches on sandbars with little or no vegetation. Least tern adults are aerial foragers that hover over shallow water in nearby river channels and floodplain habitats and dive after small fishes to feed their young. In contrast, piping plover chicks are precocious and both adults and young forage on the ground primarily along sparsely vegetated sandbar perimeters.

Spring floods of the pre-regulation Missouri River provided an annual, replenished supply of emergent sandbar habitat for tern and plover nesting. The high river stages reached during floods left correspondingly high sandbars available for nesting after flood cessation that were safe from being overtopped and destroyed by summer rainstorm pulse flows. Impoundment of the Missouri River behind mainstem dams sharply reduced upstream sources of sediment needed to create and maintain sandbars for tern and plover nesting. These poor nesting conditions resulted in loss of critical nesting and chick-rearing habitat and contributed to the listing of the interior least tern by the U.S. Fish and Wildlife Service in 1985 as endangered and the Great Plains population of the piping plover in 1986 as threatened.

The few sandbars remaining in the post-development river are topographically low because of low spring river stages. This produces an ecological trap for these birds, as sandbars attractive for nesting early in the breeding season are vulnerable to being scoured by small pulse flows later. Today, the Corps of Engineers releases small pulses (rises) from Gavins Point Dam during the pre-nesting season for terns and plovers to encourage them to nest at the highest elevations on remnant and constructed sandbars below Lewis and Clark Lake.Tributary (e.g., James River) or mainstem flow pulses have helped reduce nesting mortality during the nesting season.

Effects on Riparian Floodplain Vegetation

The pre-regulation Missouri River ecosystem was a storehouse of biological diversity maintained by a highly dynamic flow and sediment regime. The active river channel moving across its broad floodplain created enormous environmental heterogeneity and a complex mosaic of aquatic, riparian, and terrestrial ecosystems, including in-channel islands and sandbars, oxbow lakes, marshes, sand dunes, and riparian forests (see also Figure 2-4). The riparian forests were dominated by cottonwood, a pioneer species whose regeneration is dependent on the creation of sandbars during floods (and by the bar building process illustrated in Figure 2-4). Continual reworking and reforming of sandbars associated with the river channel continually created unvegetated and high sandbars for the successful nesting of least terns, piping plovers, and other riverine bird species. Expansive riparian forests on the upper Missouri River floodplain formed a successional series, with a wide age range from young cottonwood-willow forests a decade or two old occupying low benches to later successional forests dominated by green ash, box elder, and American elm on high benches old enough to have lost all traces of the cottonwood pioneer element. Cottonwood does not regenerate successfully in its own forests. Maintenance of a wide age range of forests, and hence high biological diversity, was dependent on river channel meandering and periodic widening during floods.

The Missouri River's riparian forests were greatly altered by colonizing Europeans, beginning with heavy cutting for steamboat fuel during the mid-nineteenth century, clearing for agriculture, and most recently by channelization and alteration of the river's flow and sediment regime after construction of the large dams and reservoirs (NRC, 2002). A comprehensive survey on the upper Missouri found a surprisingly rich assemblage of 220 vascular plant species growing in the floodplain forests, long after the construction of the large dams and clearing of half or more of the floodplain forest (Johnson et al., 1976; Keammerer et al., 1975).

Changes in the river's hydrologic and sediment regimes caused by the BSNP and Pick-Sloan projects have important implications for trends in river and floodplain ecosystems. For example, the cottonwood forests that remain as a legacy of the pre-regulation Missouri River cannot be sustained by the present low rates of river meandering and widening (Johnson, 1999; Johnson and Nelson-Stastny, 2006). Downstream of the large dams, however, floods still occur where levees have been removed or damaged, and cottonwoods have regenerated on flooded farm lands. In-channel nesting birds face similar prospects because of the absence of floods that historically created sandbar islands in the river that are required for their successful nesting.

DATA FOR EVALUATING MISSOURI RIVER SEDIMENT DYNAMICS

A system-wide understanding of the sources, traps, and modes of transport of sediment through the Missouri River system is important for well-informed sediment-related decisions, including but not limited to endangered species protection. The Missouri River basin historically was the focus of extensive data collection and research, and today's river managers and scientists are heirs to a remarkable legacy of prior investigations. Over time, however, as experts retired and funding diminished, the institutional memory that developed and participated directly in these programs has faded. Moreover, even though the legacy of these Missouri River sediment studies and data collection efforts is extensive and rich, there have been few efforts devoted to periodically organizing, updating, and systematically archiving this large body of information. Given the recent establishment of multiple and significant sediment-related initiatives for the river system, such as the Missouri River Ecosystem Recovery Program (MRERP and as discussed in Chapter 3), there is a clear need for a system-wide framework for better quantifying sedimentary processes.

Extensive historical data were collected by the Corps of Engineers' Missouri River Division offices in Omaha (the Omaha district office today is part of the Corps' Northwestern Division) and Kansas City. Much information on Missouri River sediment today exists in archives and earlier reports produced or sponsored by the (former) Missouri River Division of the Corps of Engineers. Today, the Corps of Engineers is the primary funding agency for the collection of sediment data in the river, but actual measurements are made by USGS investigators, working with Corps personnel. The USGS today maintains several offices along the Missouri River including Kansas City (Lee's Summit, Missouri); Columbia, Missouri; and Council Bluffs, Iowa. Important new observations and syntheses are being developed (e.g., Blevins, 2006; Jacobson et al., 2007, 2008, 2009). Many current efforts toward improved knowledge of the river's sedimentary processes are being carried out via cooperation between USGS and Corps of Engineers scientists (e.g., Jacobson et al., 2009). Notwithstanding the vast amount of sediment-related data and analyses, including these ongoing cooperative efforts between the USGS and the Corps of Engineers, there is no single, centralized, sediment database for the Missouri River.

The lack of a centralized, accessible sediment database may be inhibiting system-wide understanding of sediment dynamics. Moreover, given plans for future system-wide ecosystem management (see the discussion of the Missouri River Ecosystem Restoration Plan in Chapter 3), there will be a need for a centralized database and system-wide sediment budget as a foundation for planning, designing, and monitoring the results of various sediment management activities (see Box 2-1 for discussion of centralized data systems in the Florida Everglades and Colorado River).

An important step toward a more systematic understanding of the river's sediment dynamics would be to create a sediment budget for the entire Missouri River, from its headwaters to its mouth. The general framework for such a budget is presented in Figure 2-9. Sediment-related data for the Missouri River today are available as maps, aerial photographs and other remotely sensed imagery, hydrologic and sediment measurements, and model-based results. Creation of a centralized data management system may open new perspectives and possibilities for research and management. Such a system of course will not be created immediately; construction of a river-wide sediment budget would be useful first step.

The data in Figure 2-9 are from published reports or public presentations, provided by the Corps of Engineers and the U.S. Geological Survey. In many cases, and despite productive, useful ongoing Corps-USGS collaboration, data are still being processed and a complete summary reference is not yet available. These circumstances illustrate the need for a consistent and clearly documented database for Missouri River basin sediment. In Figure 2-9, the boxes represent sediment flux in volumes of material per year (with input data mainly from Jacobson et al., 2009).

In the course of constructing this diagram, it became clear that there are gaps regarding the archiving and organization of those data. For example, sediment data for the Missouri River exist in multiple formats (e.g., paper documents, electronic data files) and are physically located in many different offices across the basin. There are no directories listing where the data sources

BOX 2-1
DATA COLLECTION AND ECOSYSTEM MANAGEMENT IN LARGE U.S. RIVER SYSTEMS

Federal and state scientists working in other large U.S. river systems have faced similar data collection challenges that are encountered today in the Missouri River basin. Experiences from other U.S. river and aquatic systems thus may provide useful information and lessons for the Corps of Engineers, the U.S. Geological Survey, other federal agencies, and state-level managers and scientists. In particular, science and data collection programs in the Florida Everglades and the Colorado River through the Grand Canyon—and the interagency cooperation in both river systems—may be useful in informing future similar efforts for the Missouri River.

In the case of the Everglades, the Comprehensive Everglades Restoration Plan (CERP) is being executed by the Corps of Engineers and its partner state agency, the South Florida Water Management District. As in the Missouri River, restoration of the "River of Grass" in the Everglades entails huge amounts of historical data with extensive modern measurements cover a broad region. The Everglades restoration program takes advantage of a data management system that is largely under the control of the U.S. Geological Survey. The data are available in a web-based system, the South Florida Information Access system http://sflwww.er.usgs.gov/) that facilitates the sharing of available data, ranging from historical data to up-to-date monitoring data from field collections. The data include measurements, documentary data, historical reports and aerial photography, and information developed from measurements. Scientists, managers, and decision-makers have ready access through internet portals to all of the data, as does the general public. Stakeholder groups may not always agree on policies or decisions the Everglades restoration process, but they often agree on the basic data. The data generally provide an agreeable starting point for debate, which is lacking along the Missouri River.

Data management systems for the Colorado River in the Grand Canyon provide a second instructive example. The U.S. Department of the Interior conducts ecosystem monitoring along the river in Grand Canyon National Park as part of efforts to evaluate and mitigate downstream impacts of the operations of the Glen Canyon Dam. The setting is similar to the Missouri River in that one agency—the U.S. Bureau of Reclamation—is responsible for large dam operations, while another agency—the U.S. Geological Survey—is responsible for downstream ecosystem data collection. Although the data collection and evaluation program for the Grand Canyon was slow to start, and exhibited some of the same problems of diffuse and disparate data (on sediment as well as other ecological variables) that exist today in the Missouri River case, the Bureau of Reclamation made substantial efforts to centralize its data management at the behest of a National Research Council review (NRC, 1991). The effort was so successful that the U.S. Geological Survey developed a special facility for the purpose: the Grand Canyon Monitoring and Research Center (GCMRC) in Flagstaff, Arizona (see www.gcmrc.gov/). The GCMRC employs full-time data management personnel within its Information Office, which houses a geographic information system, remotely sensed data, and all data collected by the GCMRC science programs. One program especially relevant to the Missouri River is an Integrated Quality of Water Program (IQWP), which includes data collection for sediment mass-balance transport calculations for the canyon.

reside or how they might be accessed. Furthermore, the values in Figure 2-9 are products of calculations and estimates from heterogenous sources with unknown reliability. Sediment fluxes into reservoirs, for example, are based on reservoir surveys that measure some combination of coarse bed load and fine suspended load deposited into that reservoir; other boxes are based only on measurements of suspended-sediment flux. The mixing and combining of these data can lead to confusion and may blur important distinctions regarding differences in sediment sizes. Especially lacking are systematic measurements that distinguish fluxes of coarse bed-material load from finer washload. Detailed understanding of the respective fluxes of coarse sediments

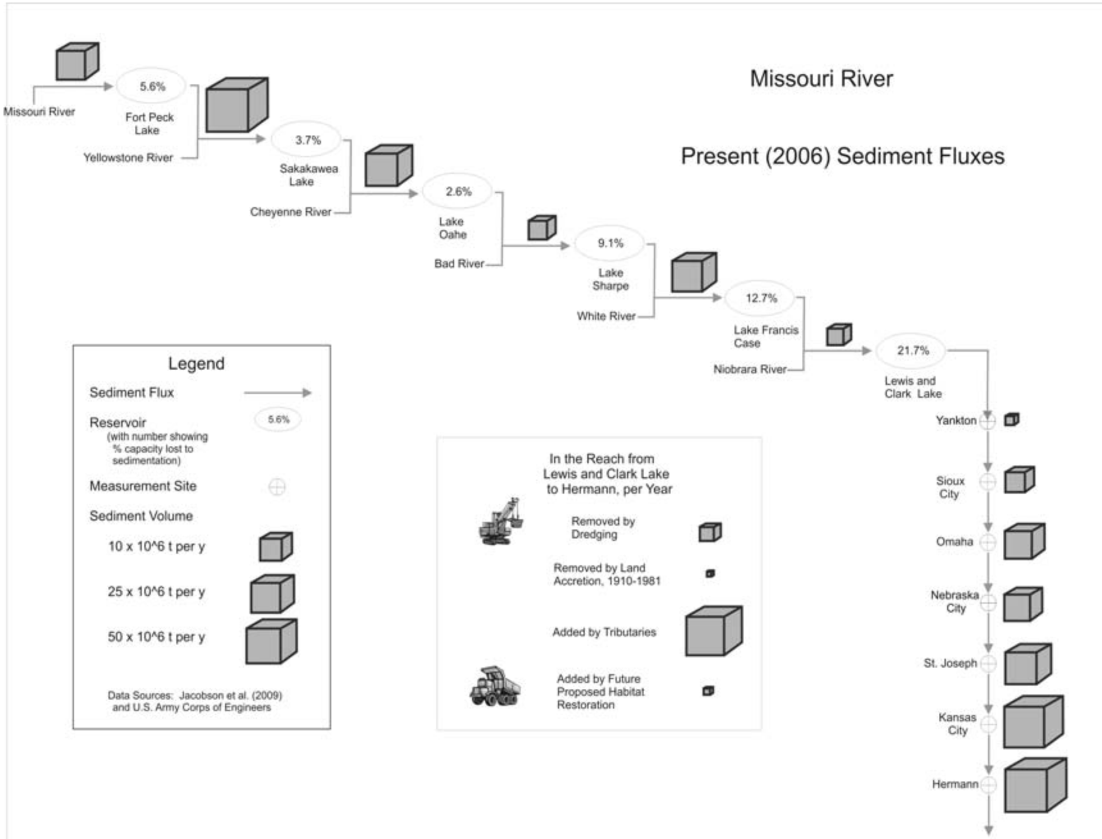

FIGURE 2-9. A generalized framework for a Missouri River sediment budget.
SOURCE: Data from Boyd et al., 2009; Hotchkiss and Huang, 1994; Jacobson et al., 2009; Stark and Pridal, 2009, USACE, 1996.

and finer sediments is fundamental information for river system managers attempting to create habitat mitigation and restoration projects both on the Missouri River and downstream as far as coastal Louisiana. An explicit and clearly-defined sediment budget for the Missouri River would, for example, help inform current debates regarding the significance of sediments deposited from Corps of Engineers habitat creation programs (discussed in further detail in Chapter 4) to the overall nutrient and sediment flux from the Missouri to the Mississippi River.

SUMMARY

Prior to channelization, bank stabilization, and the construction of mainstem dams and reservoirs, the Missouri River transported huge amounts of sediment derived from diverse watersheds throughout its drainage basin. Key source regions of sediment included clay-rich soils developed on the shale beds in the Dakotas, wind-deposited silty loess in northwestern Iowa and eastern Nebraska, the Sand Hills of central Nebraska drained by the Niobrara and Platte Rivers, and other sources in the lower Missouri River basin.

This sediment provided the building material for the river's physical structure of channels, islands, bars, and floodplains. The pre-regulation Missouri River's large sediment load and high turbidity were important to the survival and propagation of native plants, fish, and bird species. Sediment delivered to the Mississippi River was significant in building and sustaining coastal wetlands. The pre-regulation Missouri River carried a natural load of chemicals and nutrients, some of which were dissolved, some of which were attached to sediment. Of special relevance to the context of today's key Missouri River management decisions is that the river transported a natural level of phosphorus—a nutrient of broad interest today because of its role in hypoxia in the northern Gulf of Mexico. Excess sediment can be a major problem in some instances, such as in clear-water tributaries with low levels of naturally-occurring sediment and with species that evolved in less turbid environments.

Question 1 in this report's statement of task asks "How and why is sediment a significant variable in the environmental restoration of a river system like the Missouri River?"

- **Most of the historical, pre-regulation Missouri River was a sediment-rich system. However, not all tributaries of the Missouri River were sediment-rich;**
- **For many river processes and services, sediment concentrations and transport are as important as the quantity and flow of water. For example, sediment is the basic building material for river landforms that, among other things, support habitats for native riverine flora and fauna;**
- **High concentrations of sediment and high turbidity in the pre-regulation river were important to the evolution and adaptation of native species such as the pallid sturgeon;**
- **Sediment delivered from the Missouri River to the Mississippi River was historically significant in sustaining coastal wetlands in the actively accumulating lobes of the Louisiana delta.**

The Missouri River system was transformed in fundamental ways during the twentieth century. The Bank Stabilization and Navigation Project and the Pick-Sloan Plan dams and reservoirs were implemented to gain a greater degree of control over the river's hydrologic and geomorphic processes. The purposes of these structures included the goals of flood control, hydropower generation, water supply, and commercial navigation, all with far-reaching social and economic benefits. In altering the river's hydrologic and sedimentary regimes, these projects had major effects on the ecological structure of the river landscape, its vegetation communities, and the habitats for the river system's native fish and bird species. The dams and reservoirs reduced peak flood discharges, thus reducing the river's ability to erode and transport sediment downstream. The mainstem dams and reservoirs trapped large amounts of sediments that previously moved through the system and into the Mississippi River and its delta. In addition, vast amounts of sediment that previously moved episodically through the river system have been immobilized behind revetments and river-training structures along the river downstream of Gavins Point Dam.

The reduced volumes of sediment transported by the post-regulation Missouri River directly relate to one question in this report's statement of task. Question 5 in that statement asks "Are there long-term consequences to the lack of sediment in the system to the human environment, either economically or environmentally?" The answer may be summarized as:

- **Reduced turbidity;**
- **Loss of habitat for some native species;**
- **Bed degradation downstream of dams and extensively along the main channel and the lower reaches of tributaries. This causes problems for infrastructure by undermining levees and bridge foundations and lowering water levels at municipal water intakes;**
- **Reduced volumes of sediments transported downstream to the Mississippi River and delivered to the Mississippi River delta region.**

The Missouri River basin once was a site of major sediment research. Over time, however, priorities shifted, expertise on Missouri River sediment has dwindled, and there has been a decline in the attention paid to overall data collection, management, analysis, archiving, and access. Historical Missouri River sediment data are extensive, and there are important studies of sediment dynamics being conducted today in the basin, including ongoing collaborative efforts between Corps of Engineers and USGS scientists. In general, however, sediment-related data and studies are diffuse and scattered across the basin in a variety of locations and a variety of formats. A more systematic platform of sediment measurements, data archiving, and system-wide modeling knowledge will be necessary to support efficient decision making for ecosystem management initiatives.

The systems and processes for evaluating, archiving, and retrieving Missouri River sediment are fragmented and not well organized. These gaps are of special concern given plans for future investments in Missouri River ecosystem management and re-evaluation of authorized purposes for the Missouri River mainstem dams and the Bank Stabilization and Navigation Project. Effective project implementation, operations and management requires useable knowledge of sediment dynamics, including quantities and fluxes of suspended and coarse bed loads, and changes in sediment storage and resultant changes in channel morphology. More informed future Missouri River resource management decisions would benefit from a comprehensive and accessible Missouri River sediment database and sediment budget.

Corps of Engineers and the U.S. Geological Survey scientists have been conducting valuable collaborative investigations of Missouri River sedimentary processes that should be used as the foundations for a more detailed and extensive sediment budget. Over time, continued collaboration may lead to a more formal program for data collection and evaluation. The Corps and the USGS should extend their collaborative efforts and develop a detailed Missouri River sediment budget for the headwaters to the river's mouth, with provisions for continuing revisions and updates as new data become available.

3
Missouri River Governance: Institutions, Laws, and Policies for Managing Sediment and Related Resources

As discussed in Chapter 2, many of the major changes to Missouri River hydrology and sediment can be traced back to the middle of the twentieth century. Specifically, the 1944 Flood Control Act authorized the Pick-Sloan Plan and the 1945 Rivers and Harbors Act authorized the Missouri River Bank Stabilization and Navigation Project (BSNP). The goals of these projects were to: reduce floods; provide a reliable channel for commercial navigation; generate hydroelectric power; help provide water for communities along the river; and provide jobs for servicemen returning to the U.S. after World War II. The Pick-Sloan legislation included two other goals important to future management of Missouri River resources: recreation, and fish and wildlife protection. These uses over time would frequently come into conflict with the dominant interests of hydropower, water supply, navigation, and flood control. It is important to recognize that Pick-Sloan was more than an engineering infrastructure program and included authorizations for various river and reservoir system management objectives.

The lines of authority for constructing and operating these projects were relatively clear. The Corps of Engineers, under its flood control and navigation enhancement responsibilities, had extensive authority under the Pick-Sloan Plan and the BSNP. Congress assigned authority for Pick-Sloan dam construction to the Corps of Engineers. The Corps constructed hundreds of miles of revetments and levees along the river under the BSNP and also was in charge of post-construction operations and maintenance of these structures. In the years immediately after passage of Pick-Sloan and the BSNP, the Corps played a dominant role in Missouri River decision making.

With changes in laws and shifts in social preferences and priorities, the setting of decision making processes for Missouri River management has become more complicated. Notable changes in the legal setting include passage of the National Environmental Policy Act (NEPA) in 1969, the Clean Water Act (CWA) in 1972, the Endangered Species Act (ESA) in 1973, and several other environmental protection statutes. Along with this new federal legislation, recreational uses of the river were an authorized purpose of the Pick Sloan Plan, and slackwater recreation in the lakes created by the dams is accorded a high priority today by many citizens. For the Corps of Engineers, this means operating the system to meet demands of all six authorized uses—flood control, water supply, hydropower, and commercial navigation, recreation, and fish and wildlife. Examples of these latter interests include water-based recreation on the National Wild and Scenic River segments in Montana and on the National Recreational River segments in Nebraska and South Dakota, which were developed in response to the National Wild and Scenic Rivers Act of 1968. Moreover, under the Endangered Species Act the Corps must comply with legal requirements to protect federally listed native species from extinction as a consequence of their actions and recover and maintain their populations by removing or lessening threats of their actions to the species' survival. Additionally, under the 1934 Fish and Wildlife Coordination Act, federal agencies were required to mitigate for habitat loss due to water development projects. The 1934 act was specifically applied to the Missouri River under the 1980 Fish and Wildlife Coordination Act Report and became the origin of the Missouri River Mitigation Program (described later in this chapter).

Congress expects Corps of Engineers dam and reservoir system operations to reflect these multiple goals. In that regard the Missouri River Master Water Control Manual (Master Manual) was prepared by the Corps in 1960. The most recent Master Manual update was released in March 2006, after consultation with user groups and agencies of governments across the basin. The change was motivated by the desire to meet authorized purposes and newly emerging demands on the system, but more importantly to be in compliance with a Biological Opinion of the U.S. Fish and Wildlife Service that focused on the habitat needs of three endangered species.

Today, decisions about how to manage the river's dams, reservoirs, navigation channel, and other resources are guided by an extensive body of laws, agency guidance documents, budgets, and river users who can voice their preferences through the political process. In some instances conflicts among users and among agencies with conflicting missions are resolved through court rulings. This report refers to the collective body of these interrelated laws and policies as the "governance system" for Missouri River management.

This chapter describes the current governance system, how it has changed and become more complicated over time, and the challenges this presents today to the Corps and other parties. Consistent with this report's statement of task, its focus is on sediment-related issues. In many ways the Corps remains the focal point of Missouri River management; but as this chapter describes, its authority to make decisions is now shared with others, especially the U.S. Fish and Wildlife Service.

This chapter provides background for understanding Missouri River governance that is discussed in the report's subsequent chapters. In doing so, it broadly describes relevant laws, institutions, and policies for managing Missouri River sediment and related resources. It also provides advice relevant to question 7 in the report's statement of task regarding improved management strategies.

MISSOURI RIVER MANAGEMENT, THE CORPS OF ENGINEERS, AND SHARED DECISION MAKING

The process of submitting management plans for review by others is not new to the Corps of Engineers. Nevertheless, the influence of that review process on Corps decision making has increased over time. This chapter highlights the many laws, organizations, and manuals that guide and govern Corps of Engineers decision making, beginning with one of the earliest requirements—compliance with the Fish and Wildlife Coordination Act.

Fish and Wildlife Coordination Act

Passed in 1934, and amended in 1946, 1958, 1978, and 1995, the Fish and Wildlife Coordination Act (or the "Coordination Act") was designed to promote preservation and enhancement of fish and wildlife by requiring equal consideration of their habitat needs in conjunction with federal participation in water resource development. The act authorizes the U.S. Fish and Wildlife Service (FWS) to make recommendations for modifications in project design or operation to benefit fish and wildlife resources. Federal agencies like the Corps must give full consideration to the FWS recommendations, as well as any recommendations made by the agency exercising administration over the wildlife resources of the affected state. The Coordination Act also specifies that water development project plans include such justifiable measures for wildlife conservation, as determined by water management agencies, to obtain maximum overall project benefits. Thus, as a procedural requirement, the Corps must receive and fully consider recommendations from the Fish and Wildlife Service and state wildlife agencies; however, acceptance of the recommendations is at the discretion of the Corps.

This is not to suggest that the Coordination Act has had limited influence. In fact, the earliest efforts to address habitat losses associated with river development, especially the BSNP, were initiated as a result of the act. In the early 1980s the Fish and Wildlife Service, executing its comment responsibilities under the Coordination Act, reported that the BSNP had significantly reduced fish and wildlife habitat, caused fish and wildlife population declines, and the loss of recreational opportunities (USFWS, 1980). In order to mitigate these effects, the Congress directed a Corps study that resulted in the 1984 report, "Missouri River Bank Stabilization and Navigation Project, Final Feasibility Report and Final EIS for the Fish and Wildlife Mitigation Plan." The Missouri River Mitigation Plan was subsequently authorized under the Water Resources Development Acts of 1986 (Public Law 99-662) and expanded in 1999 (Public Law 106-53). The primary activity under the mitigation plan is acquiring land from willing sellers and then developing aquatic and terrestrial habitat throughout the project's length by dredging filled-in areas, reopening historical chutes, bank stabilization, dike notching, pumping, dike/levee construction, and vegetative plantings. The Mitigation Project plan calls for the development of 166,750 acres of land in separate locations along the river in Nebraska, Iowa, Kansas and Missouri. The Corps began implementing the mitigation plan in 1991. As of September 2009, 56,606 acres of Missouri River floodplain land have been acquired from willing sellers within the four states. Total costs, including land acquisition, planning, engineering and design, habitat development, construction management, operation and maintenance during construction, and monitoring, totaled $132,792,000 through 2006 (USACE, 2006). The mitigation plan continues and has become an integral part of the larger Missouri River Recovery Program (MRRP), or additional programs being carried out or planned under new authorities, such as the Missouri River Ecosystem Restoration Program (MRERP) that was authorized under WRDA 2007 (see below).

The Wild and Scenic Rivers Act mandates preservation of the "outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural, or other similar values" of free-flowing, designated rivers. River segments can be designated as wild, scenic, or recreational. Congress declared its intent to protect the natural features of the Missouri River by designating several river segments under this Act. In the upper reaches of the river in Montana, a 64-mile segment below Fort Benton, Montana has been designated as wild and another 85 miles as scenic or recreational. Further downstream, a 39-mile segment from Fort Randall Dam to Lewis and Clark Lake, which straddles South Dakota and Nebraska, has been designated as a recreational river. Additionally, a 59-mile river segment downstream from Gavins Point Dam also has been designated as a recreational river. Together, these segments comprise significant portions of the remaining unimpounded river in the upper basin, and their islands, sandbars, chutes, and snags that retain some of the river's former dynamic character.

National Environmental Policy Act

The National Environmental Policy Act (NEPA) was enacted in 1969. The act required all federal agencies, including the Corps, to prepare analyses that assess and report on proposals for major federal actions with significant environmental impacts. The NEPA process provides a significant mechanism for information sharing, public involvement and comment by other agencies of governments at all levels. In passing this act, Congress expected that no federal agency decision would be made without a thorough understanding of environmental impacts and alternatives. The National Environmental Policy Act thus demands attention to its procedural requirements to gather, receive, and consider advice on the effects of a range of reasonable alternatives to the proposed federal action. The act does not, however, dictate which alternative the agency must choose, and it does not require the federal action agency to act upon the advice of other agencies or the public. The National Environmental Policy Act and the Coordination Act are similar in that the Corps must solicit input, and must consider carefully the information received, but need only take it into consideration when making decisions.

Yet, like the Coordination Act, the NEPA process can have great influence on the decision made. As discussed in greater detail below, revisions made to the Corps operations of the dam and reservoir system and as described in the so-called Master Manual, required an environmental impact statement. The processes and procedures required by NEPA created both a forum for debate and for public and interagency review and comment on technical analyses. The Corps' Record of Decision, which explains the basis for its decision to adopt the Master Manual, includes commitments to future actions that have since been implemented and that do govern the way the Corps manages the river, including habitat creation actions that go beyond those included in the Missouri River Mitigation Plan.

Endangered Species Act

The federal Endangered Species Act (ESA), passed in 1973, puts responsibility on federal action agencies to comply with, not just consider, recommendations of federal wildlife agencies to minimize or avoid the impact of federal activities on endangered species. Also, the U.S. Fish and Wildlife Service may specify steps that need to be taken to recover populations of a species when the Fish and Wildlife Service demonstrates that past activities of the action agency contributed to the species decline. The process by which this decision is made and then agreed to by the FWS and the affected federal agency (in this instance the Corps) follows a well defined set of steps.

Under Section 4 of the Endangered Species Act, the U.S. Department of the Interior (or Department of Commerce) is authorized to list species as endangered or threatened and to designate critical habitat. Once listed, no person may "take" the species by killing it or otherwise harming it, and no federal agency may take an action that jeopardizes the continued existence of the endangered species or that modifies its critical habitat. Moreover, the federal agency must consult with the Fish and Wildlife Service, then must demonstrate to the satisfaction of the Fish and Wildlife Service that the proposed actions will not jeopardize the continued existence of the species or adversely modify their critical habitat. If the Fish and Wildlife Service issues a finding of jeopardy in its biological opinion, it will recommend reasonable and prudent alternatives (RPA) designed to accomplish the objectives of the action in question without causing jeopardy. Federal regulations define a reasonable and prudent alternative as an action that: (1) can be implemented in a manner consistent with the intended purpose of the action; (2) can be implemented consistent with the scope of the action agency's legal authority and jurisdiction; (3) is economically and technologically feasible; and (4) would, the Fish and Wildlife Service believes, avoid the likelihood of jeopardizing the continued existence of listed species or resulting in destruction or adverse modification of critical habitat (see Code of Federal Regulations (CFR) Title 50, Section 402.02).

A decision to deviate from reasonable and prudent alternatives recommended by the Fish and Wildlife Service will not in and of itself violate the Endangered Species Act, but it may expose the action agency to the risk of penalties or injunctive relief in the event that a court finds a violation of the jeopardy prohibition. Clearly the Endangered Species Act is different from the Coordination Act not only in focus, but also in the way it allows the Fish and Wildlife Service to place conditions on the Corps' exercise of its congressional authorities to operate the Missouri River dam and reservoirs system. This is one way in which the decision making on Missouri River management today has broadened.

A biological opinion issued by the Fish and Wildlife Service in 2000 under authority granted by the Endangered Species Act, along with a supplemental opinion in 2003, has directed Corps of Engineers habitat construction plans and other activities along the Missouri River—especially downstream of Gavins Point Dam.

Fish and Wildlife Service Biological Opinions under the Endangered Species Act

For two decades or more, the Corps of Engineers and the Fish and Wildlife Service have consulted on Missouri River dam and reservoir operations under the Master Manual and with regard to species of interest (also see USACE, undated), under the Endangered Species Act, as well as the Coordination Act. In April 2000, the Corps of Engineers asked the Fish and Wildlife Service to consult under the Endangered Species Act with regard to Master Manual revisions, including: (1) operations of the Missouri River mainstem system, (2) related operations of the Kansas River tributary reservoirs, and (3) operation and maintenance of the Missouri River Bank Stabilization and Navigation Project. The Corps had identified four listed species in the project area: the endangered pallid sturgeon (*Scaphirhynchus albus*), the endangered least tern (*Sterna antiallarum*), the threatened piping plover (*Charadrius melodus*), and the threatened bald eagle (*Haliaeetus leucocephalus*).

The Corps Biological Assessment in early 2000 concluded that its operations of the Missouri River Main Stem System, and related operations of the Kansas River Tributary Reservoirs, and operations and maintenance of the Missouri River Bank Stabilization and Navigation Project were detrimental to the survival and recovery of the endangered pallid sturgeon and interior least tern, the threatened northern Great Plains population of the piping plover, and the bald eagle. The Fish and Wildlife Service and the Corps then entered into a formal consultation process in April 2000 to address effects of the Corps operations of the Missouri River on the listed species.

The Fish and Wildlife Service determined through the consultation process that Corps Missouri River operations posed jeopardy to the continued existence of the listed species. The two agencies then collaborated to develop a Biological Opinion, and in 2000 the Fish and Wildlife service issued a Biological Opinion that contained a description of current river operations, current status of the species, an environmental baseline, and a conclusion that the referenced Corps actions were likely to jeopardize the continued existence of the least tern, piping plover, and pallid sturgeon, but would not jeopardize the bald eagle. The Fish and Wildlife Service further concluded that to avoid jeopardizing the continued existence of the tern, plover, and sturgeon, it was necessary to: (a) restore a portion of suitable riverine aquatic habitats and hydrologic conditions necessary for successful reproduction and recruitment of the three listed species, and (b) provide population augmentation (in the near-term) for the pallid sturgeon to ensure genetic viability of the species until the necessary habitat and hydrologic conditions are restored.

The Fish and Wildlife Service, working with the Corps, defined a Reasonable and Prudent Alternative deemed necessary to avoid jeopardizing the least tern, piping plover, and the pallid sturgeon. The following text summarizes those Reasonable and Prudent Alternative elements relevant to this report's sediment-related tasks. Flow enhancement below Fort Peck Dam, unbalanced system regulation, and pallid sturgeon propagation are described elsewhere (USFWS, 2000).

Flow Enhancement Below Gavins Point Dam. Implementation of a spring rise and summer drawdown from Gavins Point Dam (river mile 811) was required by the Service to achieve four outcomes: 1) provide a spawning cue to pallid sturgeon; (2) condition new and existing emergent sand bar habitat for tern and plover nesting and chick rearing and adjacent shallow, slow-water habitat needed by both birds and fishes; (3) enhance aquatic habitat through connection of the main channel to backwaters and side channels to increase nutrients, invertebrates, and forage fish for larval and juvenile pallid sturgeon and adult and young least terns; and 4) scour sediments from pallid sturgeon spawning areas to increase the likelihood of egg survival.

Habitat Restoration/Creation/Acquisition. The Fish and Wildlife Service directed the Corps to restore a portion of the historical Missouri River habitat to benefit the listed birds and fishes. Broad habitat restoration targets of 20-30 acres of shallow water per mile were defined, although the goals varied by river segments for emergent sandbar habitat (ESH) and shallow water habitat (SWH).

Adaptive Management/Monitoring. The Corps was directed to implement an adaptive management process that allowed modification of management actions to benefit listed species in response to new information and to changing environmental conditions. One component of this process was establishment of an Interagency Coordination Team (ACT) to coordinate and guide development and implementation of a robust monitoring program to better understand baseline conditions, analyze actions, and implement modification as necessary to improve results.

*Recognize the Role of Sediment in Species Recovery. M*ost importantly for this report, the Biological Opinion recognized that sediment input was necessary to restore instream habitats and turbid waters:

> Initially, the Corps should determine the sediment deficit from natural conditions and the functional quantities needed to restore instream sandbars, and implement a pilot project at one of the main stem dams. . . . The Corps also should restore turbidity to functional levels downstream of Fort Peck, Fort Randall, and Gavins Point Dams. Turbidity will increase with actions taken to restore sediment transport; however, additional measures may be needed if reintroduced sediments are clean of small particulate matter that needs to be resuspended (USFWS, 2000..... p.213 pt. IV.B.)

The Fish and Wildlife Service issued a Supplemental Biological Opinion in 2003 that considered habitat conditions and new information not considered in the 2000 Biological Opinion (for details of the 2003 Biological Opinion see USFWS, 2003). The 2003 Biological Opinion governs the operation of the system today. Key changes from the 2000 Biological Opinion include accelerated construction of shallow-water habitat (with a research, monitoring, and evaluation adaptive management component) and modified flow enhancement requirements (Chapter 4 describes current approaches to habitat restoration and adaptive management).

THE MASTER MANUAL AND FLOW MODIFICATION: SHARED DECISION MAKING THROUGH THE NEPA PROCESS

The Master Manual is the guide used by the Corps to operate the system of six dams on the Missouri River Mainstem Reservoir System. It describes the six reservoir Mainstem Reservoir System, including its Water Control Plan, and establishes operational policy for the multiple project purposes of flood control, hydropower, water supply, water quality, irrigation, navigation, recreation, and fish and wildlife. The Corps first undertook revision of the original 1960 Master Manual in 1989 when the basin was experiencing its first major drought since the system became operational. Additionally, federal listing of the interior least tern, piping plover, and pallid sturgeon underscored the need to revisit the Master Manual. The Corps also became more aware of its responsibilities to tribes as independent sovereign nations. The Corps' objectives for the Master Manual were to develop a Water Control Plan to meet the contemporary needs of the basin, fulfill responsibilities to tribes, and comply with environmental laws, including the ESA. The 2000 and 2003 Biological Opinion were released in the midst of Master Manual revisions.

Several Water Control Plan features were changed in the Master Manual, and these changes became part of the preferred alternative identified in the required Environmental Impact Statement (EIS) was issued in 2004. As one example, the preferred alternative included minimum flows for periods when navigation was not supported to provide for downstream power plants, municipal and industrial intakes, water supply and water quality. An adaptive management process was also identified. However, because it was coincident with the Master Manual revision process, the Biological Opinion influenced but did not dictate decisions on operational rules. For example, the Biological Opinion called for a bimodal spring pulse release from Gavins Point Dam. Although the environmental impact statement addressed several alternatives that included spring pulse releases, the preferred alternative selected in the Corps Record of Decision (ROD) for the revised Master Manual did not include such releases. However, the ROD agreed that a spring pulse plan that would comply with provisions of the 2003 Amended Biological Opinion would be identified no later than 2006. Although the Record of Decision was challenged by various states and environmental groups, in the end this plan was adopted (Jacobson and Galat, 2008).

NEW STUDIES, NEW ORGANIZATIONS, CHANGING RESPONSIBILITIES

The environmental impact statement and the updated Master Manual committed to the Corps to a new program in 2004, known as the Missouri River Recovery Program (MRRP) as well as creation of a stakeholder advisory group, the Missouri River Recovery Implementation Committee (MRRIC). The MRRIC was formally established through the federal Water Resources Development Act (WRDA) of 2007. To aid in the recovery effort, Congress also authorized the Missouri River Ecosystem Plan, or MRERP, under the 2007 WRDA (and described below in further detail). Subsequently, in 2009 Congress instructed the Corps to begin the Missouri River Authorized Purposes Study (MRAPS).

Each of these authorities and studies bear some relation to decisions and planning being done under the Master Manual, the Biological Opinion, and the ongoing mitigation plan. Meanwhile, in 2007 the Missouri Clean Water Commission ordered the Corps to stop discharging sediments into the mainstem Missouri River during construction of mitigation projects along the river (the 2007 order was amended in March, 2008). All these programs and institutions are described below.

Missouri River Recovery Program

In its 2004 Master Manual, the Corps committed to a different approach to Missouri River decision making. The Master Manual record of decision (ROD) commits the Corps to river restoration actions that will be identified, reviewed, and implemented through a cooperative process that includes stakeholder representation and adaptive management. This Missouri River Recovery Program is a comprehensive effort, led by the Corps in partnership with the Fish and Wildlife Service, tribes, states, other federal agencies and nongovernmental organizations, to develop and implement actions to recover the Missouri River.

The MRRP vision is for, "*a sustainable ecosystem supporting thriving populations of native species while providing for current social and economic values*." Its mission is to: "*implement actions to accomplish Missouri River ecosystem recovery goals in coordination and collaboration with agency partners and stakeholders*." Recovery efforts are coordinated by the Corps with funding that flows through the Corps budget (see: http://www.moriverrecovery.org/mrrp/f?p=136:1:749223002111673::NO:::. for details on the MRRP).

The Corps of Engineers is expected to coordinate a variety of restoration activities while undertaking floodplain acquisition, habitat creation, river flow modifications, and research and assessment. The largest current recipients of Corps funding under the Biological Opinion are the Independent Science Program (ISP) and land acquisition under the ongoing Mitigation Program.

Missouri River Ecosystem Restoration Plan

The Missouri River Ecosystem Restoration Plan was authorized under the 2007 Water Resources Development Act for the purpose of conducting a collaborative, long-term ecosystem restoration study. Under MRERP, the Secretary of the Army, in consultation with a stakeholder advisory group (MRRIC), will conduct a study of the Missouri River and its tributaries to determine actions required to: (1) *restore* ecosystem functions, (1) *mitigate* habitat losses, and (2) *recover* native fish and wildlife on the Missouri River (see Box 3-1 for details on restoration, mitigation, and recovery concepts and definitions).

The goal of the MRERP is to recommend priorities and objectives for Missouri River recovery, mitigation, and restoration while seeking balance with social, economic, and cultural values for future generations. Key socio-economic values proposed for consideration include: navigation, water supply, flood attenuation, power generation, recreation, and cultural resources. MRERP objectives include: (1) considering ongoing programs related to mitigation, recovery

BOX 3-1
Definitions of Mitigation, Recovery and Restoration Currently Used Within the MRERP

Mitigation *consists of measures to avoid, minimize, or compensate for adverse impacts to the environment.* The U.S. Army Corps of Engineers follows mitigation provisions including the Water Resources Development Act of 1986, Water Resources Development Act of 2000, Water Resources Development Act of 2007 (33 USC 2283), and Council on Environmental Quality regulations (40 CFR 1500–1508) implementing the National Environmental Policy Act. The Council on Environmental Quality regulations (40 CFR 1508.20) provide the basis of mitigation *as a means to avoid or minimize environmental harm. This includes measures to rectify, reduce, eliminate, or compensate for the impacts caused by the action.*

Recovery is defined under the Endangered Species Act as *"improvement in the status of listed species to the point at which listing is no longer appropriate"* under the criteria set out in Section 4(a)(1) of the Act" (50 CFR 402.02).

Restoration consists of separable features undertaken to return a degraded condition to a less degraded condition (ER 1105-2-100, Appendix C, Corps Planning Guidance Notebook (USACE 2000)). The Corps of Engineers' civil works ecosystem restoration policy (ER 1165-2-501 (USACE, 1999) states that "the purpose of Civil Works ecosystem restoration activities is to *restore significant ecosystem function, structure, and dynamic processes that have been degraded. Ecosystem restoration efforts will involve a comprehensive examination of the problems contributing to the system degradation, and the development of alternative means for their solution. The intent of restoration is to partially or fully reestablish the attributes of a naturalistic, functioning, and self-regulating system."* The intent of ecosystem restoration is to reverse the adverse impacts of human activity and restore ecological resources, including fish and wildlife *habitats*, to previous levels of productivity but not a higher level than would have existed under natural conditions in the absence of human activity or disturbance (ER 1105-2-100, Appendix C (USACE, 2000)).

(Sources: Wayne Nelson-Stastny; USFWS MRNRC Coordinator; Randy Sellers, USACE, Kansas City District, MRERP coordinator)

and restoration; (2) identifying priorities for mitigation, recovery and restoration throughout the basin; (3) outlining a long-term adaptive management approach for restoration of the river, and; (4) guiding future program and site-specific action development to ensure that overall restoration goals are met in the long term. An environmental impact statement is being developed for a comprehensive watershed plan that identifies priorities for ecosystem restoration in the Missouri River Basin to be implemented by the Corps, the FWS, and others. The preferred alternative from this environmental impact statement will guide future recovery efforts throughout the Missouri River Basin. The present deadline for completion of the MRERP study and publication of the final MRERP-EIS and Record of Decision is 2016.

The scope of MRERP is broader and more integrative than past programs. It includes the mainstem Missouri River and its alluvial valley (floodplain) from Three Forks, Montana, to its confluence with the Mississippi River near St Louis. Additionally, tributaries, bluff lands and uplands may be added as necessary to consider targeted resources.

Missouri River Recovery Implementation Committee

In the Water Resources Development of 2007, the Secretary of the Army was directed to establish a Missouri River Recovery Implementation Committee (MRRIC) composed of federal, state, tribal, and non-governmental stakeholders. The MRRIC's duties are to provide guidance on the Missouri River Ecosystem Restoration Program. Specifically, the MRRIC is to provide guidance to the Secretary of the Army on Missouri River recovery and mitigation plans. The MRRIC has roughly 70 members who represent a wide array of local, state, tribal, and federal interests throughout the Missouri River basin. The committee has 28 seats that represent 16 non-governmental stakeholder categories. In addition, eight states and 28 tribes have voting members. Thirteen federal agencies with programs affecting the Missouri River appoint non-voting representatives to MRRIC.

The purpose and scope of the MRRIC is threefold. First, the MRRIC makes recommendations and provides guidance on the Missouri River Ecosystem Recovery Plan, which, as noted above, includes *mitigating* losses of aquatic and terrestrial habitat, *recovering* federally listed species, and *restoring* the Missouri River ecosystem to prevent further declines among other native species. Second, the MRRIC provides guidance on the Missouri River Recovery Program. This guidance includes changes to their implementation strategies as a result of lessons learned in the course of adaptive management, as well as coordination of the development of consistent policies, strategies, plans, programs, projects, activities, and priorities. Lastly, the MRRIC's recommendations must identify potential impacts to stakeholders and means of avoiding, minimizing, or mitigating adverse impacts.

The MRRIC has made recommendations for an engagement strategy between it and the Corps on the MRERP. Most relevant to this report, the MRRIC recommended that the study include sediment and river morphology dynamics throughout the basin, including: channel degradation; sediment levels below reservoirs; and the relationship of sediment deposition on the functionality of reservoirs (Missouri River Recovery Implementation Committee, Recommendations on Purpose and Need, Adopted by Consensus on July 23, 2009).

The MRRIC also concluded that the MRERP study provides an exceptional opportunity for a coordinated, basin-wide approach between federal, tribal, state and stakeholder interests. MRRIC advised the Corps to identify a single, comprehensive and integrated plan to guide the implementation of programs associated with mitigation, recovery and restoration activities in the Missouri River Basin. It further advised that the Secretary rely on the MRRIC as the principal forum for discussing and adopting final provisions of this coordinated, basin-wide plan. The role of the MRRIC in influencing Corps' decisions is evolving, and it is too early in its history to assess how it will affect federal policy for the Missouri River.

Missouri River Authorized Purposes Study

As noted at the beginning of this chapter, legally authorized Missouri River uses include: flood control, navigation, irrigation, hydropower, water supply, water quality, recreation, and fish and wildlife. For years there have been differences of opinion and conflicts over how to best use the water and related resources of the dam and reservoir system among its many users. In addition to more traditional purposes and use of the system, the ongoing Biological Opinion and the Missouri River Ecosystem Restoration Plan focus attention on native species protection and recovery. There is a great deal of competition for the river's resources and great interest in the many trade-offs among its various authorized purposes (Chapter 7 provides further comments regarding trade-off choices and resource limits).

Against this background, in the Omnibus Appropriations Act of 2009, Congress authorized the Corps to conduct the Missouri River Authorized Purposes Study (MRAPS). The act directs the Secretary of the Army to review the original project purposes of the Flood Control Act of 1944 to determine if changes to the authorized project purposes and existing federal water resource infrastructure may be warranted. The study was begun in October 2009, with an authorized cost of $25 million, and is scheduled to be completed in five years (more information on the study is available at: http://www.mraps.org/). The study is independent of the Missouri River Recovery Program and MRRIC; however, given the substantial overlap among MRAPS, MRRP, and MRRIC, clarification of lines of authority may be necessary.

THE CLEAN WATER ACT, STATE WATER QUALITY RULES, AND SEDIMENT

In considering sediment management on the Missouri River, it is important to understand not only provisions of the Endangered Species Act, but also provisions of the Clean Water Act (CWA), especially the setting of ambient water quality standards for sediment and phosphorus concentrations. In many settings and river systems across the country, as well as in some streams throughout the Missouri River basin, sediment is considered to be a pollutant. As such, discharge of sediment is subject to regulatory limits, and reducing sediment runoff is a focus of many agricultural management practices.

Under the Clean Water Act, states are responsible for setting water quality standards that meet the broad goals of the act: restoring and maintaining the chemical, physical, and biological integrity of the nation's waters. Water quality standards begin with state identification of designated uses for each state waterbody. Once designated uses are set, the state adopts measurable criteria that ensure that designated uses are met. These criteria may be narrative or numeric. Narrative criteria are descriptive of desired biological conditions for a river. Numeric criteria specify the acceptable frequency, duration, and magnitude of the presence of a pollutant (e.g., turbidity measure, phosphorus concentrations) or a waterbody condition (benthic or fish community index). In addition, the criteria are expected to be protective of downstream waters. Although states are responsible for water quality criteria, the Environmental Protection Agency (EPA) is expected to exercise oversight on criteria. In interstate waters, such as the Missouri River, EPA can lead efforts to harmonize uses and criteria among states.

The Clean Water Act and Corps of Engineers Missouri River Mitigation Projects

In an order issued in September, 2007, and later amended in March, 2008, the Missouri Clean Water Commission (CWC) ordered the Corps to stop discharging sediments into the Missouri River, as the Clean Water Commission found that these discharges would violate the state of Missouri's water quality standards (also see Perry, 2007). The Corps interprets the Biological Opinion as requiring it to increase turbidity in the river and hence it is encouraged if not mandated, pursuant to the Endangered Species Act, to discharge sediments for habitat mitigation projects into the river. Generally speaking, the commission accepts that the Biological Opinion calls for habitat construction, but that it does not require discharge of sediments into the mainstem Missouri River.

As will be discussed in detail in Chapter 6, it is possible to develop water quality criteria that are consistent with the Clean Water Act and that do not conflict with Biological Opinion requirements for the Missouri River. For example, closer investigation of the legislative history and origins of the Clean Water Act show that it long has been recognized that historic watershed conditions can be a template for setting water quality uses and criteria. The Senate Report that accompanied the original Clean Water Act legislation refers to the "natural...integrity" of the nation's waters, and highlights "the importance of historical records on species composition, ecological studies, and estimations of what a 'balanced natural ecosystem' should look like" (S. Rep. No. 92-414, reprinted in 1972 U.S.C.C.A.N. at 3716. Similarly, the 1972 House Report describes "integrity" as "a condition in which the natural structure and function of ecosystems is maintained" (H.R. Rep. No. 92-911, at 76 (1972), reprinted in Congressional Research Service, A Legislative History of the Water Pollution Control Act Amendments of 1972, at 763 (1973).

Current understanding of the historic sediment and related nutrient conditions in river segments and in the tributaries, as described in Chapter 2, provides just such a template. That chapter lays a foundation for interpreting the rules governing discharges of sediment to the river. As was explained in Chapter 2, sediments differ in their characteristics, the sources of sediments differ, and sediment and nutrient history of each segment and each tributary is different. It therefore would be expected that not only would water quality criteria differ across segments and tributaries, but also rules governing sediment discharges would differ as well. In "clear water segments," sediment discharges would be limited by regulations that apply to all sources. In segments where the historic reference condition suggests sediment loads of certain grain and nutrient composition, then discharges consistent with those criteria would be allowable. However, if the segment-specific and tributary-specific criteria are to be met, then under the Clean Water Act, rules governing sediment discharges appropriate to that receiving water will apply uniformly to all sources of sediment, including sources from private lands, public facilities, and Corps of Engineers restoration activities.

SUMMARY

Congress continues to create authorities and responsibilities that leave the Corps effectively as the "water master" of the Missouri River, and hence sediment manager, as well.

Congress authorized the Corps to execute MRERP and the authorized purposes study, and propose plans to update and synchronize the multiple legislative directives under which the Corps now operates. Meanwhile, Congress created MRRIC to strengthen shared decision making, but MRRIC has only recently begun its operation and its roles and responsibilities have yet to be clarified. The role of MRRIC in relation to the role of the Corps will need to be defined within the setting of occasional cross-purposes of river users, limits of the river's resources to meet all user demands, and the increasing powers and responsibilities of multiple federal, state, and tribal agencies granted by environmental laws, especially the ESA.

In the decades immediately following authorization of the Pick-Sloan Plan, the Corps of Engineers played a clear role as the water master of the Missouri River and its dam and reservoir system. Today, however, the setting of Missouri River governance is very different. For example, several recent, major river management initiatives and studies—such as the 2000/03 Biological Opinion and the mitigation program—have added greatly to compliance requirements for the Corps. In addition, states, tribes, commercial interests, and nongovernmental organizations today seek a more active voice and role in river management decisions. At the same time, the Corps of Engineers retains authority to operate the Missouri River dam and reservoir system. These many changes have complicated the Missouri River governance structure for the Corps and others as they try to reach agreement on programs such as Biological Opinion program implementation, broader ecosystem recovery, and sediment management planning.

The Missouri River Recovery and Implementation Committee has the potential to play a central role in building consensus among a broad group of federal agencies and stakeholders in matters related to water and sediment management. To help realize that potential, the Secretary of the Army should periodically review the MRRIC mission statement, operational rules and accomplishments, implement modifications to the mission, rules and operations as deemed appropriate, and report its results to the Congress.

4
Sediment and Current Ecological Restoration Activities

The Corps of Engineers has implemented numerous projects along the Missouri River under the 2000/03 Biological Opinion to improve habitat for endangered, native bird and fish species. The projects are grouped into two programs within the overarching Missouri River Recovery Program (MRRP) described in Chapter 3: emergent sandbar habitat (ESH) projects mainly for the benefit of bird species, and shallow water habitat (SWH) projects mainly for the benefit of pallid sturgeon. These projects entail dredging, movement, and placement of sediment in order to construct or create sandbars or chutes, or to make structural adjustments in engineered projects, such as notching a levee. The Corps of Engineers began constructing many of these projects less than ten years ago. Some monitoring and evaluation efforts have followed. Given the slow response times of complex ecosystems with long-lived species to management actions, the monitoring and evaluation programs can be considered relatively young.

In addition to the ESH and SWH projects, there are four other components of Biological Opinion compliance under the MRRP: mitigation, flow modification, a cottonwood management plan, and science (Figure 3.1). Under the mitigation program, lower Missouri River floodplain lands are purchased from willing sellers and many SWH projects are constructed in these areas. The Gavins Point Dam "spring rise" flow modification component of the Biological Opinion in part is intended to redistribute channel sediments and contribute to SWH and ESH creation and maintenance. The cottonwood forest management plan identifies newly deposited sediments as sites for cottonwood regeneration. Lastly, the science program is intended to conduct the monitoring and research within an adaptive management framework to evaluate the integrated contribution of ESH, SWH, mitigation lands, cottonwood regeneration, and flow modifications towards meeting the Biological Opinion Reasonable and Prudent Alternatives (RPA) and recovering listed species and the ecosystem upon which they depend. This chapter focuses on the prominent ESH and SWH projects, but it is important to recognize that the ESH and SWH programs are implemented within the larger Missouri River Recovery Program and that they have important ecological and institutional linkages with these other MRRP programs.

This chapter addresses point 7 in this report's statement of task, which asks:

Are current Corps' management strategies, restoration tools (e.g., channel widening, creation of chutes, shallow water habitat, etc.), and other activities adequate and comprehensive *enough to address issues associated with sediment and nutrients in the system? If not, how might such strategies and activities be improved?"*

The 2000/03 Biological Opinion specifies the use of an adaptive management strategy to implement, evaluate, and adjust mitigation projects for endangered species. The topic also is frequently referenced in related initiatives and guidance documents for the MRRIC and the MRRP. This chapter thus begins with discussion of the concept and practice of adaptive management.

ADAPTIVE MANAGEMENT ALONG THE MISSOURI RIVER

Adaptive Management Concepts

In its 2000 Biological Opinion, the U.S. Fish and Wildlife Service directed the Corps of Engineers to implement adaptive management to promote flexibility of management actions in response to new information and changing environmental conditions to benefit the listed species:

> The Corps should embrace an adaptive management process that allows efficient modification/implementation of management actions in response to new information and to changing environmental conditions to benefit the species…
>
> This approach embraces the uncertainties of ecosystem responses and attempts to structure management actions to best address those uncertainties, recognizing that learning is a critical outcome. Adaptive management is viewed as a continuous process of actions based on testing, evaluating, informing, and improving… It will be the basis from which the Service can identify and evaluate performance (FWS, 2000).

Adaptive management therefore has an overarching importance and role in Corps of Engineers Missouri River programs for endangered species and related sediment management actions and programs.

The 2003 Reasonable and Prudent Alternatives (RPA) from the Fish and Wildlife Service present three elements of an adaptive management plan: an Agency Coordination Team (ACT); an endangered species and habitat monitoring program; and an annual reporting requirement. Additionally, the charter of Missouri River Recovery and Implementation Committee (MRRIC) acknowledges that adaptive management will play a role in Missouri River resources management. It defines adaptive management as:

> A type of natural resource management in which decisions are made as part of an ongoing science-based process. Adaptive management involves testing, monitoring, and evaluating applied strategies and incorporating new knowledge into management approaches that are based on scientific findings and the needs of society. Results are used to modify management policy, strategies, and practices.

> The purpose of adaptive management is to help meet environmental, social, and economic goals, increase scientific knowledge, and reduce tensions among stakeholders (MRRIC, 2008).

The adaptive management concept is widespread in the environmental management literature and in several prominent ecosystem restoration programs. Much of the conceptual thinking behind this concept derives from three seminal texts: Holling (1978), Walters (1986), and Lee (1993). Adaptive management can be broadly defined as:

> Adaptive management is a decision process that promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather emphasizes learning while doing. Adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions among stakeholders (NRC, 2004).

The adaptive management concept and its applications have been discussed in numerous forums and publications. There is no single definition, and the term leaves room for interpretation.[1] A common feature among many of these programs is recognition and implementation of an adaptive management cycle that follows an iterative linked series of steps: (1) assess and define the problem; (2) identify management options, (3) implement alternative management actions, (4) monitor responses to these actions, (5) assess results, and (6) adjust or revise management actions based on learning (for a variety of adaptive management definitions, interpretations, and applications, see: Ledwin et al., 2008; Nichols and Williams, 2007; Rogers, 1998; Ruhl and Fischman, 2010; Walters, 2000; and Williams et al., 2002). Adaptive management principles are being applied to several large-scale aquatic ecosystem restoration programs in the United States including the Everglades (CERP, 2008), the Colorado River (GCMRC, 2001), and the Platte River (PPRIP, 2008).

The adaptive management paradigm and its operational components present an attractive management approach in settings like the Missouri River: large geographical extent; many ecological uncertainties; numerous stakeholder groups, some of whom have very different preferences; and no clear, simple path ahead for the management of this system and its many resources. Indeed, in many ways an adaptive approach in such

[1] Additional references regarding adaptive management and its definitions and applications include Gregory et al., 2006; Gregory and Long, 2006; Lyons et al., 2008; Nichols and Williams, 2006; Rogers, 1998; Ruhl and Fischman, 2010; Walters, 2000; and Williams et al., 2002.

settings is inescapable, and there is a compelling rationale behind the notion of acknowledging uncertainties, the need to take action in the face of unknowns, learn from management actions, keep options open to the extent possible, and seek ways to maintain and promote flexibility in physical systems and decisions.

Just as there is no single definition, there is no single, widely-accepted set of operational principles. However, the Department of the Interior Adaptive Management Technical Guide (Williams et al., 2007) addresses this challenge by recommending nine operational steps grouped into set-up and iterative phases. Goals and objectives will be site specific and shaped by environmental conditions, stakeholder preferences, and prevailing laws and policies. In defining overall program goals (or 'ends'), and the means employed to reach those goals, it is important to distinguish between the two. Failure to clearly distinguish ends from means can lead to inappropriate trade-offs, misleading performance tracking, and overly prescriptive management strategies (Failing and Gregory, 2003). Adaptive management processes and components are employed not as ends in themselves, but rather as means for achieving larger goals, such as reducing jeopardy by contributing to self-sustaining populations of a listed species.

A recent background document for Missouri River recovery discusses the challenges associated with a long-term, viable adaptive management program:

> Perhaps the primary challenges raised concern long-term commitment to ecosystem monitoring, data analysis, and adherence to a decision framework that incorporates scientifically based thresholds for change in management actions. That is the "iterative phase" of adaptive management and it may take decades. However, most agencies are subject to much shorter funding cycles that rarely mirror scientific recommendations for monitoring ecosystem development following management actions.
>
> Additionally, the costs of adaptive management may be high because quality data collection and management are labor-intensive activities. Some exceedingly complicated adaptive management programs have been determined to be prohibitively expensive prior to implementation. Committing funds to experimental management actions is sometimes perceived as a risk. However, these costs should be weighed against the costs of failure to achieve restoration and recovery goals if an adaptive management approach is not used.
>
> (Diefenderfer and Fleming, 2008).

One upshot of these questions and realities is that formal adaptive management programs require years, if not decades, to implement, evolve, and mature. Moreover, the adaptive management paradigm will not eliminate environmental uncertainties and unknowns, nor will it necessarily resolve differences and disputes among stakeholder groups. Even in areas of the nation where adaptive management has been practiced explicitly for many years—such as in the Colorado River below Glen Canyon Dam and in the Florida Everglades—there is a need for more monitoring; environmental surprises still occur; laws, policies, and priorities shift; and stakeholders have differing priorities and points of view.

Although the adaptive management learning-by-doing approach is appealing, in large-scale, high profile programs—such as the North American waterfowl adaptive harvest management plan (Nichols et al., 2007), some (but not all) components of the Everglades restoration program (CERP, 2010) and Glen Canyon flow release experiments (Melis et al., 2010)—there are few examples of unambiguous successes[2] Possible explanations are that adaptive management is often invoked in resource management contexts without clear articulation of what decisions need to be made, a clear definition of learning, how success or effectiveness is measured, how to choose among potentially conflicting values and priorities, and how to use results from monitoring and research to reduce uncertainty and implement change in often entrenched monitoring programs.

Perhaps more frequently encountered than clear-cut successes are evaluations of why adaptive management did not work as anticipated. These case studies can provide insights for the MRRP and MRRIC to avoid or redress similar pitfalls [see Walters (1997, 2007) for discussion of several institutional challenges in adaptive management programs]. Decision makers often fail to comprehend the need for management experiments when they appear to contradict conventional wisdom or obvious intuition. Decision makers often are reluctant to acknowledge uncertainty in making policy choices and may lack the necessary authority to carry out the complicated administrative steps involved in planning and implementing new and complex management programs.

The scientific knowledge bases where adaptive management has been applied have been improved through more monitoring and collaborative discussions, and experiments have enabled stakeholder groups to gain appreciation for respective points of view. The adaptive management principles of incorporate stakeholder, manager, and scientist inputs into setting objectives, implementation, monitoring, and program adjustment can improve efficiencies in terms of costs, communication, and scientific advances.

Corps of Engineers Adaptive Management Actions and Strategies

The 2000/03 Biological Opinion and Development of Adaptive Management Guidance

One observation in the implementation of adaptive management actions and programs to enhance the habitat of Missouri River endangered species is that there has been a mismatch between, on the one hand, the large amount of resources devoted to ESH and SWH project construction activities along the river and, on the other hand, the relatively modest efforts aimed at development of adaptive management guidance, protocols, performance goals, and stronger science-based monitoring and evaluation to guide and learn from that ongoing project construction.

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[2] Some small-scale forestry projects have shown success at achieving adaptive management objectives (e.g., Marmorek et al., 2006).

The need to take decisive actions to improve habitat in accord with the Biological Opinion is understandable, and a tenet of adaptive management is that actions often need to be taken in the face of uncertainties. At the same time, mitigation and restoration actions (i.e., means) that are not guided by a larger programmatic structure that includes ecologically-relevant performance goals (i.e, ends) run the risk of being uncoordinated and possibly result in wasted expenditures and frustrations among stakeholders and budget authorities. Along the Missouri, only after years of project construction and considerable expenditures were preliminary adaptive management guidance documents initiated (Diefenderfer and Fleming, 2008; Thom et al., 2009). In addition, the Corps established an Adaptive Management Cooperation for Recovery (CORE) Team in October 2009, which currently is preparing a framework for an Adaptive Management Process using the Department of the Interior Adaptive Management Technical Guide (Williams et al., 2007) to guide the overall Missouri River Recovery Program (MRRP) at achieving the Biological Opinion Reasonable and Prudent Alternative (RPA) elements. This group is also drafting specific adaptive management plans for the emergent sandbar habitat and shallow water habitat. Currently, these plans include two phases (Fleming, 2009). Phase 1 will apply adaptive management steps and principles to implementation of ongoing Biological Opinion reasonable and prudent alternative elements, including ESH and SWH programs and specific projects within them (e.g., creation of a specific sandbar or channel chute). Phase 1 also proposes to develop adaptive management decision support tools (models, analyses, information reports), and work with decision makers and stakeholders to develop a learning process. Phase 2 has been identified as addressing the Missouri River Ecosystem Restoration Plan (MRERP) and its environmental impact statement process.

Performance Objectives for Restoration Projects

Part of the reasonable and prudent alternative developed in the 2000/03 Biological Opinion called for restoration of “a portion of suitable riverine aquatic habitats and hydrologic conditions necessary for successful reproduction and recruitment of the three species” (USFWS, 2003). Monitoring and evaluation efforts of the RPA to date have largely addressed compliance with the Biological Opinion targets of acres of shallow water habitat and emergent in-channel sandbar habitat (USFWS, 2003). Although a metric of ‘acres created’ may have relevance and importance for improving conditions for endangered species, such a single, areal metric is limited in that it does not consider the numerous population-level variables that affect life cycles and histories of Missouri River endangered species. Performance metrics such as targeted tern fledgling ratios that are currently part of the least tern program, or targeted pallid sturgeon age-class structure (not currently part of the pallid sturgeon population monitoring program) would represent more ecologically relevant outcomes of management actions that can inform decision makers about whether habitat creation is supporting self-sustaining populations of listed species.

The Corps of Engineers is implementing two major habitat mitigation programs along the Missouri River: the emergent sandbar habitat (ESH) project and the shallow water habitat (SWH) project. The following section discusses details of implementation and monitoring efforts associated with those projects.

EMERGENT SANDBAR AND SHALLOW WATER HABITAT PROJECTS

As explained in Chapter 2, a longstanding goal of engineering activities along the Missouri River channel downstream of Sioux City, Iowa has been to stabilize river banks and maintain a channel with adequate depth to support commercial navigation. The Corps of Engineers constructed hundreds of miles of dikes and revetments to this end, much of it accomplished under the 1945 Bank Stabilization and Navigation Project (Box 4-1 defines the many types of river engineering structures that have been used along the Missouri). Dikes extending from the floodplain into the channel were constructed to constrict river flows and produce a single channel. The dikes also resulted in accretion of sediment to form new floodplain areas, reducing channel width. Revetments were installed to reduce bank erosion, reduce shoreline sediment input, and fix the channel in place. By 1950, 59 percent of dikes and 69 percent of revetments had been constructed. By 1970, 95 percent of both dike and revetment construction had been completed (USACE, 1980). By 1980, levees were constructed along most of the length of the channel to protect the existing and newly accreted floodplain lands from floods (USFWS, 1980).

In response to shifting social preferences and federal environmental laws, the Corps of Engineers began to modify some river engineering structures in the 1970s to improve habitat for riverine fishes. The 1986 Water Resources Development Act (WRDA) authorized the Bank Stabilization and Navigation Fish and Wildlife Mitigation Project, under which the Corps of Engineers implemented projects to restore habitat lost due to the BSNP. This mitigation project, which was amended in the 1999 WRDA, is not species-specific but addresses channel-floodplain habitat rehabilitation for the benefit of overall ecosystem biodiversity. Some of the mitigation project sites overlap with projects being implemented under the Biological Opinion (Bittner and Bell, 2010).

Emergent Sandbar Habitat

In response to the 2000/03 Biological Opinion, the Emergent Sandbar Habitat (ESH) program was initiated in 2004. The project area extends from Garrison Dam in North Dakota downstream to Sioux City, Iowa. The ESH project areas include reservoir reaches and remnant floodplain areas, including the National Park Service's Missouri National Recreational River in Nebraska and South Dakota (Figure 4-1). The endangered least tern and piping plover depend on bare sandbars for successful nesting and fledgling (USFWS, 2003). Because such habitat is limited along the river, and because bare sandbars will become vegetated without scouring flows, the Corps of Engineers is increasing the extent of ESH by creating new sandbars largely from dredged material and by clearing vegetation from existing sandbars. The removal of early-succession woody vegetation from sandbars to provide habitat for terns and plovers may conflict with other Corps of Engineers programs to enhance cottonwood forest establishment on islands and floodplains, and the Corps has recognized the need to coordinate this program with its other programs that enhance cottonwood forest established on islands and floodplains (USACE, 2010).

BOX 4-1
ENGINEERING STRUCTURES ALONG THE MISSOURI RIVER

Levee: an earthen embankment running parallel to and near the channel bank, intended to hold floodwaters within the channel and protect floodplain lands outside the channel from inundation. Virtually the entire lower river section is leveed, and some sites have two or more levees.
Revetment: a structure running on and along the channel bank, intended to prevent erosion of the bank. Commonly built of wood or rock.
Dike (also called wing dike or jetty): a structure extending from the bank part way into the channel, intended to focus high velocity flows within a narrow central portion of the channel, to scour the bed and maintain adequate water depth for navigation. Today within the BSNP area, almost all bends of the river have a field of dikes on the inside bank of the bend and revetment along the outside bank of the bend.
Constructed chute: In the Missouri River, the term chute refers to almost any secondary channel that is connected to the main channel (at both ends) and carries flow either year-round or seasonally. Chutes were naturally occurring features of the river, but many were eliminated by construction of the BNSP. Constructed chutes are created by excavation of inactive chutes, or by digging entirely new chutes on the floodplain. They are commonly several thousand feet long. They are intended to provide lower-velocity, shallower, more complex habitat than the main navigation channel.
Constructed backwater: a linear, branched, or oblong depression on the floodplain, connected to the main channel at one end only and holding water either year-round or seasonally. They provide areas of low velocity that serve as refuge for fish and other organisms during high flows, and shallow water habitat during other seasons.
Revetment chute or pilot channel: a trench along the revetment between the revetment and the floodplain bank, formed by excavation or by erosion during floods that fills with water and becomes aquatic habitat. Notches often are cut into the revetment to increase hydraulic connectivity of the revetment chute and the main channel.
Bank notch: a notch cut in an existing dike along the bank, typically one in each dike within a dike field. They are intended to create a secondary channel along the bank that is faster than typical flow within the dike field.
Type B notch: a notch cut into an existing dike and the adjacent bank, with most of the notch cut into the bank. Intended to allow some bank erosion, increase top width of the river, and increase diversity of depth and velocity within the dike field.
Dike notch: a notch cut in an existing dike, allowing water flow through the gap. Scour holes and shoals or sand bars form downstream of the gap, creating diversity of water depth and velocity intended to benefit aquatic species.
Major dike modification (dike lowering and chevrons): Existing dikes are lowered to a level below typical water level within the channel and extending back into the bank, and chevrons are constructed between the dikes at the channel edge of the dike field. Dike lowering is intended to allow bank erosion and increase channel top width. A chevron is a V-shaped structure built of rock, with the point of the V at the upstream end and a gap at the point, intended to create a sandbar downstream of the chevron, create scour and deposition on the bank side of the chevron, and direct flows toward the navigation channel to reduce shoal formation.

River sandbars are labile landforms created in disturbed environments. Their morphology fluctuates with cycles of erosion and deposition, and even without erosion or deposition their surface area alternates between aquatic and terrestrial environments as river stage fluctuates seasonally. Hydrogeomorphic processes of flow, sediment erosion, and deposition provide disturbance mechanisms that strongly affect the rate at which a sandbar becomes a permanent vegetated island (Corenblit et al., 2007).

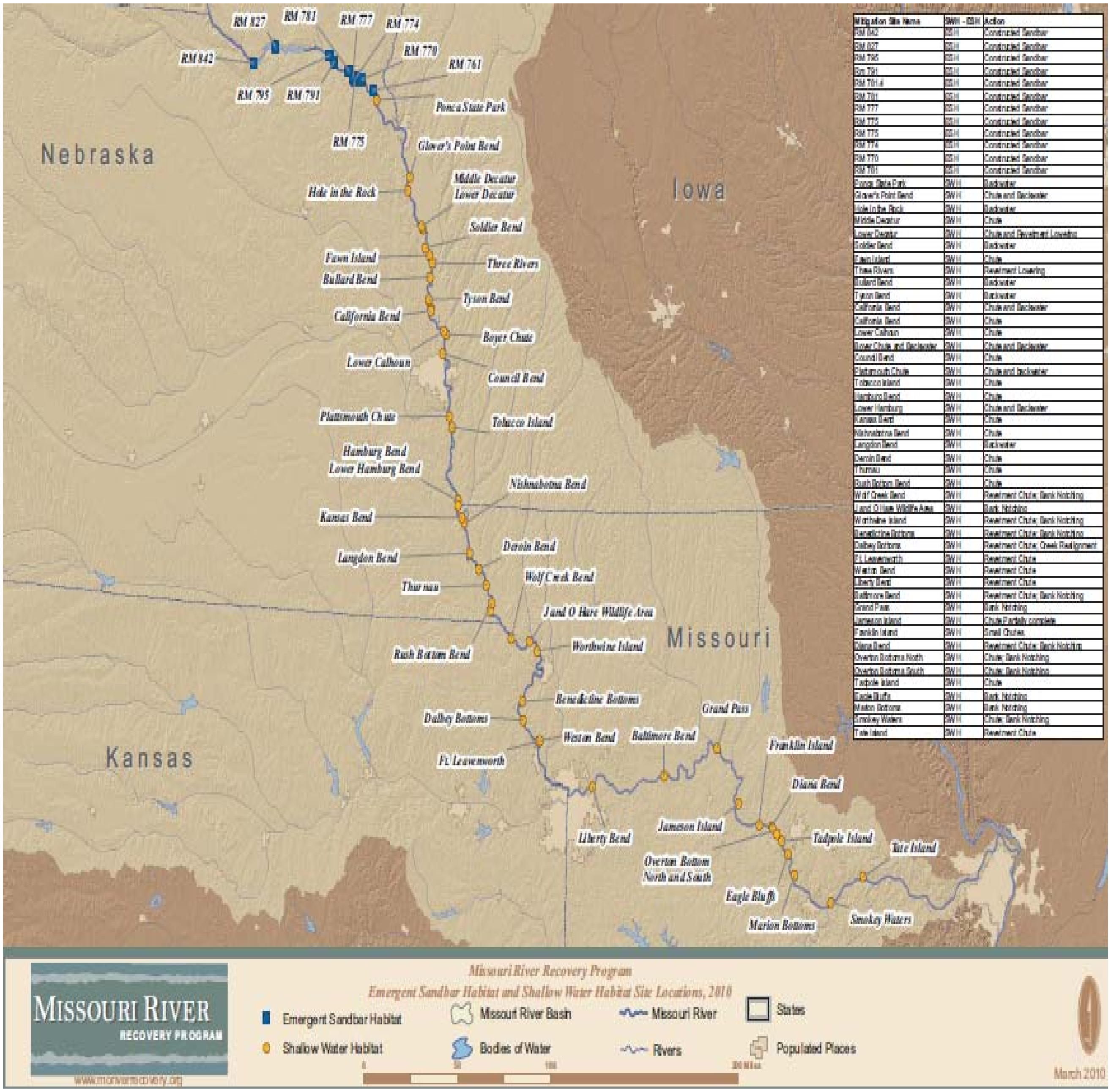

FIGURE 4-1 Missouri River Recovery Program Emergent Sandbar Habitat and Shallow Water Habitat Projects.
SOURCE: Gossenauer, 2010, personal communication. Provided by Michael Gossenauer, USACE.

Prepublication Copy

Sandbars provide the environmental conditions for vegetation establishment (Dixon, 2003; Gurnell and Petts, 2002; Johnson, 2000). However, bare sandbars also contribute unique ecological value to a diversity of biota within the active channel of large rivers. Exposed bare substrate characteristic of sandbars is important to nesting riverine turtles (Plummer, 1977) and roosting (Kinzel et al., 2009) and nesting birds (Smith and Renken, 1991), and shorebirds use recently exposed sandbar shorelines for feeding. As described in Chapter 2, the pre-regulation Missouri River channel was characterized during summer by large expanses of shifting, open, unvegetated sandbars or emergent sandbar habitat. This habitat is important for nesting and foraging by the two endangered bird species on the Missouri River today, the interior least tern and the northern Great Plains population of piping plovers.

An important issue in the context of this report is how the construction of sandbars affects the sediment regime of the river. When emergent sandbar habitat material is derived from the river bed, there is no net impact on the river sediment budget. Over a few years, the bar will be eroded and the sediment will re-enter the river bed. This change takes place against the backdrop of reduced sediment transport in the twentieth century due to both sediment storage behind the dams and to stabilization of formerly temporary storage sites, such as bars and banks, due to reduced cut-and-fill alleviation associated with flood cessation and reduction (NRC, 2002).

Under the 2003 Amendment to the Biological Opinion, the Corps is required to maintain specified acreages of natural sand bar habitat "through flow regulation or other means" (USFWS 2003 Biological Opinion Amendment, p. 194) and to create ESH when targets cannot be met in other ways. The acreage required varies, depending on the reach, from 10 to 40 acres per river mile in 2005, increasing to 20 to 80 acres per river mile by 2015. The characteristics of the natural and created ESB habitat are specified in terms of sediment size, vegetation and detritus cover, and bar size and shape. Current rates of ESH creation are not adequate to meet Reasonable and Prudent Alternative targets in the Biological Opinion for habitat creation (USACE, 2010a, App. A), due to a variety of reasons including construction challenges, vegetation re-growth, and potential impacts on adjacent private lands.

Shallow Water Habitat

The Corps' Shallow Water Habitat program aims to create habitat considered necessary for the recovery of endangered pallid sturgeon. These habitats are important nurseries for many young-of year riverine fish species, providing rich invertebrate forage, escape from predation by larger fishes that cannot access the shallows, and refugia from fast mid-channel flows. Fine organic matter that forms the base of the aquatic food web and coarse organic matter (large woody debris) that is important as cover for small fish tend to accumulate in shallow water areas. Shallow water habitat was abundant along channel margin and sandbar shorelines in the historical Missouri River channel, but most was lost with channelization and bank stabilization below Sioux City, Iowa. What remains has been identified by the Fish and Wildlife Service as critical habitat for recovery of pallid sturgeon.

Under the 1986 Bank Stabilization and Navigation Fish and Wildlife Mitigation Project, the Corps of Engineers began constructing chutes and backwaters in 1991 along the main channel in an effort to restore shallow water habitat. As of 2001, these projects have been incorporated within the SWH project under Biological Opinion compliance.

The Reasonable and Prudent Alternatives specified in the 2000/03 Biological Opinion required reconstruction or rehabilitation of 20 percent of the shallow water habitat that existed prior to the construction of the Bank Stabilization and Navigation Project. The SWH project area extends from near Ponca, Nebraska downstream to the mouth of the Missouri at St. Louis. Plans are to ensure that 20 to 30 acres of shallow/slow-water habitat per river mile exist below Ponca, Nebraska by 2020 to meet this requirement.

The 2003 amended Biological Opinion defined shallow water habitat as locations with water depths less than 5 feet (<1.5m) and water velocities less than 2 feet-per-second (<0.6 m/s) (USFWS, 2003). Natural shallow water habitats in the Missouri River include side-channels, backwaters, submerged sandbar and bankline margins, and low-lying depressions in the floodplain adjacent to the channel. Using natural shallow water habitat as a model, constructed shallow water habitats under the revised definition are expected to have a predominance of shallow depths intermixed with deeper holes and secondary side channels, lower velocities, and higher water temperatures than main-channel habitats. The criteria for depth (<1.5 m) and for velocity (<0.6 m/s) may be modified as understanding of large-river ecology improves. The shallow water habitat structures in the main channel aim to enhance habitat diversity by creating zones of higher and lower flow through dike fields and in chute-like areas behind dikes and revetments.

Two types of shallow water habitat projects are being constructed: habitat creation at the margins of the navigable portion of the main river channel, and construction or modification of chutes and backwaters on floodplains (Missouri River Recovery Program, 2010). Construction of shallow water habitat at the channel margin can be accomplished through a variety of structures and techniques, such as notching dikes and building wing dikes (Box 4-1 lists additional approaches that could be used).

Constructed chutes are intended to be hydrologically connected to the main channel at both high and low flows, have active bed sediment transport, and provide habitats that mimic historical depth and velocity conditions. Chutes provide shallower, more complex habitat than is found within the navigation channel. Constructed backwaters are connected to the main channel at only one end, and therefore provide habitat with lower flow velocities. Chutes are designed to evolve over time, developing sinuosity and sandbars. Both chutes and backwaters will develop more natural, vegetated banks than the main channel since their banks are largely unprotected by revetments or dikes.

Chutes and backwaters require floodplain lands for construction, and they have been implemented only on public lands, including some land previously in state or federal ownership and land newly acquired under the 1986/99 Mitigation Project and the U.S. Fish and Wildlife Service Big Muddy Fish and Wildlife Refuge. The Mitigation Project authorizes the Corps to acquire roughly 166,000 acres of floodplain land from willing sellers by 2042 (Bell and Bitner, 2010). As of September 2009, approximately 56,000 acres—or 34 percent—of the authorized total acreage had been acquired (ibid.). Through these programs, land will be acquired and available for habitat creation projects (although not all of this area will be converted to flooded habitat).

As chutes and backwater areas are constructed on the floodplain, excavated sediment is either deposited directly in the river or piled on adjacent banks. As a chute evolves after construction, widening and/or lateral migration will deliver most or all of the sediment piled on the bank to the flow. In addition, the chute will trap some sediment in bars. The result is a net addition of sediment to the river during construction and the early post-construction adjustment phase. Over time, with lateral migration and additional sinuosity, erosion within the chute is likely to be roughly balanced by deposition. Backwater areas do not experience significant flows, and any excavated sediment deposited on their banks is less likely to be introduced into the river. Flow into and out of the backwater during high flow periods, as well as maturation of the banks, may introduce minor amounts of sediment into the flow, but overall the net effect of constructed backwaters will be to trap sediment from transport in the main channel.

The use of chutes to enhance habitat diversity and promote river and ecosystem restoration is a relatively new practice, and there is only a small body of existing projects or research findings that could be used to guide Missouri River chute construction and adjustments. An example of Missouri River-specific studies is being led by USGS scientists and their work on river corridor habitat dynamics (see Jacobson et al., 2004b for evaluation focused specifically on Missouri River chutes). Beyond the Missouri, chute projects have been implemented and evaluated in Europe (see Buisje et al., 2002). The limited amount of past projects and substantive research results lends support for the adaptive approach to these projects that is being promoted by the USGS, the Corps of Engineers, and others.

MONITORING ESH AND SWH PROJECT OUTCOMES

As described in the first part of this chapter, monitoring the effectiveness of restoration activities is a building block of adaptive management. In general, effectiveness monitoring of restoration projects is intended to determine whether the project is producing the desired ecosystem conditions and outcomes stated in the project goals. Monitoring should be driven by a series of related questions, such as:

- Are habitat restoration actions successful at creating the kinds of habitat that species need? Which actions are most successful?
- Are populations of the target species increasing?
- Are populations of the target species well-distributed?
- If so, are the population increases and distribution the result of habitat creation activities, or related to other causes?
- Are constructed habitats functioning such that they will increase fledgling success, or other performance measures? If so, what specific characteristics of the constructed environment are responsible?

Other related questions also may need to be addressed. For example, an adaptive management program may have developed a model of how the ecosystem functions (conceptual ecosystem model). If the life cycle and habitat needs of the target species are not adequately understood, monitoring may need to provide answers to questions such as “What habitats are the target species using and when? Are there specific habitat characteristics that are critical to successful species use?”

Monitoring of both target species and habitat characteristics, such as water depth, water quality, primary production or food availability, thus is important, and the two aspects need to be coordinated so that linkages are understood. Events and conditions outside of the project may influence species response, and monitoring of control sites (sites where no habitat creation is done) is typically used to sort out these factors. Habitat creation may have effects on other organisms and aspects of the ecosystem, so a broader data collection effort may be necessary to address this issue. In a dynamic environment like the Missouri River, the question of persistence of created habitat over time is important. It is unlikely that any created habitat will last for many decades without repeated maintenance, but better knowledge of differences in short- to medium-term persistence (less than one reproduction season vs. a decade) among alternative designs would be useful in designing more efficient habitat restoration.

Emergent Sandbar Habitat

In 2007, the Corps of Engineers began development of a monitoring plan designed to evaluate the effectiveness of the emergent sandbar habitat program (USACE, 2008). Before 2007, monitoring consisted primarily of determining numbers of least terns and piping plovers and nests by habitat type (USACE 2007, 2008). Monitoring was not designed to yield the type of information on effectiveness of restoration activities needed to adjust those activities under adaptive management. The new monitoring plan is intended to integrate monitoring of biological response (tern and plover nesting, nest fate and fledging; invertebrates) and physical habitat characteristics of constructed ESH, to determine whether the ESH program (including both the bar construction and vegetation clearance methods) is increasing least tern and piping plover habitat (Sherfy et al., 2008). Analysis of the ESH program through a Programmatic Environmental Impact Statement (PEIS) is underway and a Final PEIS and Record of Decision (ROD) are expected in late 2010 (USACE, 2010c). In addition, a study to determine effectiveness of various vegetation removal techniques, such as mowing, spraying herbicides, and mechanical removal, has been underway for several years, and is projected to be available in Fall 2010 (USACE, 2010a). One gap in the ESH program is the absence of information evaluating ecological benefits and physical persistence of constructed sandbars. A report from an independent consulting team involved in ESH program design and implementation found that a database of “lessons learned” in the planning and implementation of individual projects would be beneficial (GeoVal, Inc., 2009a).

The proposed design for new ESH construction and monitoring (USACE, 2010c) holds promise to better integrate various elements of the program and support a more structured adaptive management approach to ESH goals. Improvements in the ESH program are especially important given that an independent evaluation team has determined that the 2015 ESH acreage goals cannot be met, due to both logistic and financial challenges (GeoVal. Inc., 2009). Moreover, it remains to be seen if habitat proves to be the primary limiting factor to recovering tern and plover populations along the Missouri River.

Shallow Water Habitat

Shallow Water Habitat projects in the main channel, such as dike notching, bank notching or chevrons, have been monitored under the Habitat Assessment and Monitoring Program (HAMP) since 2004. HAMP monitoring includes both biological response (fish species composition and richness) and habitat response (water depth, velocity and substrate) to SWH creation, with sampling designed to relate these two components. The HAMP monitoring follows a standard approach in ecological monitoring: a comparison of before-project conditions with after-project conditions, and comparison of river bends with projects to those without projects. The main findings to date are that fish use of SWH is highly variable in project and control reaches (Sampson and Hall, 2009). It therefore is not yet possible to draw clear conclusions about biological effectiveness of the monitoring or the projects.

An independent science review of the HAMP research design found that the monitoring design was sound, but that statistical design and support were inadequate, and monitoring implementation was not strongly based on conceptual models (Sustainable Ecosystems Institute, 2005). Further, it was found that sampling methods had varied from year to year, making it difficult to produce useable results. In response to the review, in 2007 and 2008 the Corps simplified and standardized the HAMP sampling methods (USACE, 2008). The independent review also suggested that physical habitat monitoring be better integrated with biological monitoring (ibid.).

Another limitation of the HAMP monitoring program has been the lack of overall, synthetic assessment. Monitoring is conducted separately for the Omaha and Kansas City districts, and there is no overall synthesis and interpretation of results from the two districts. Furthermore, as in the case of the ESH program, it is not clear that physical habitat monitoring is designed to evaluate alternative methods of creating SWH to support adaptive management. Understanding both the physical and biological outcomes of these projects is crucial to an adaptive management process. As in the ESH program, the engineers themselves recognized the need for evaluating effectiveness of SWH creation. For example, a study of the SWH program found that a "lessons learned" database on SWH projects would be beneficial (GeoVal, Inc., 2009b). This suggests a need for more detailed monitoring (whether formal or informal) and assessment of shallow water habitat creation activities.

Shallow water habitat is also created through construction of chutes off the main channel, originally as part of the Missouri River Fish and Wildlife Mitigation Project. Monitoring results of this project for 2006-2008 are summarized and analyzed in a 2009 report (Sterner et al., 2009), which includes monitoring of both fish response and geomorphic/habitat response. This report may be more useful for adaptive management than the HAMP reports, as it includes conclusions about what strategies are most effective and recommendations for future project design and implementation. In addition to the formal Missouri River Recovery Program monitoring programs (see http://www.moriverrecovery.org/mrrp/f?p=136:1:3775197112319747) and in the annual Corps of Engineers Biological Opinion reports (USACE 2007, 2008, 2009, and 2010a), several studies of geomorphology, physical habitat, hydrology and ecological evolution of natural and created chutes have been conducted by scientists from outside the Corps of Engineers (Jacobson et al., 2004a; Jacobson, 2006).

Toward More Systematic, Hypothesis-Directed Monitoring and Evaluation

One observation of the ESH and SWH programs is that the processes and programs for monitoring outcomes of these restoration projects have been slow to start, spotty, and incomplete, making it difficult to draw conclusions about successes and progress. Also, there is little evidence that the products of the monitoring programs are being used to evaluate the performance of habitat restoration projects—a key element of the Biological Opinion Reasonable and Prudent Alternatives—towards reducing jeopardy to the listed species. The research and monitoring reports from the ESH and SWH programs tend to include raw data tables, but little analysis of project status (e.g., success, failure, or in need of modification). For example, annual Corps of Engineers Biological Opinion reports (USACE 2007, 2008, 2009, and 2010a) have thus far largely addressed compliance with the (RPA) metrics of acres created of emergent sandbar and shallow water habitat. The ‘acres created’ metric may be an important variable, but its causal connection to the fundamental objectives (‘ends’) of population increases of the listed birds and sturgeon remains untested. There also is a need to consider broader ecological outcomes of the projects, such as short-term changes in physical river conditions or longer-term changes in species populations. As mentioned, these annual reports contain a great deal of data, *but they lack evaluation of those data that are relevant and necessary to understand if compliance actions are reducing jeopardy to the listed species.*

Missouri River endangered bird and fish species are affected by numerous environmental factors. For example, pallid sturgeon survival and reproduction are affected by water temperature, predation, illegal harvest, contaminants, invasive species, sediment reductions, habitat availability, and magnitude of seasonal floods, among others (Wildhaber et al., 2007). The relative importance of each factor and how their importance rankings may change over time are not adequately known. Current research and monitoring programs emphasize physical habitat factors such as flow velocity and water depth which represent only a small subset of potentially causative factors.

Especially lacking is the development and use of formalized conceptual models that organize and consolidate information in order to represent what is known or hypothesized about the effects of multiple environmental factors (stressors) on the listed species. Conceptual ecological models (CEM) also can be used as a construct or platform to articulate alternative, even competing hypotheses, involving the expected effect of habitat construction projects on habitat conditions and the demographics of listed species. Some initial products involving conceptual models are now available for pallid sturgeon (Bajer and Wildhaber, 2007; Wildhaber et al., 2007), the piping plover (Plissner and Haig, 2000), emergent sandbar habitat (Ledwin et al., 2008), and for Missouri River riparian vegetation (Dixon et al., 2010). Further development and application of these approaches and models will lead to better understanding of the relative importance of environmental variables on the life cycles of endangered species. These models also will be useful in gauging the effectiveness of management actions, such as the ESH and SWH projects, and in promoting the propagation and recovery of endangered species.

To date, however, these efforts have been not been conducted or employed as part of larger, system-wide management strategies by the Corps of Engineers, the Fish and Wildlife Service, and other entities working on Missouri River recovery programs. The foundation of recovery efforts on the Missouri River, especially those directed at protecting and enhancing endangered species habitat, will be strengthened by further development and use of these conceptual ecological models. This will promote more systematic evaluation and learning of the relative influences of multiple variables on the life histories and cycles of endangered species.

SUMMARY

The Corps of Engineers has been constructing numerous ESH and SWH projects along the Missouri River as directed by the 2000/03 Fish and Wildlife Service Biological Opinion. The Corps is seeking to implement and operate those projects according to principles of adaptive management as recommended in the Biological Opinion. The Corps responded to the Biological Opinion mandates by beginning ESH and SWH project construction, especially after the 2003 Biological Opinion amendment. The Corps also has been monitoring the ESH and SWH projects and developing adaptive management guidance documents.

Adaptive management is an attractive paradigm for managing large complex ecosystems like the Missouri River system. It is being pursued elsewhere in the nation and the world. In some instances it has proven to be a useful management paradigm and "it may be particularly suited to large, complex ecosystem restoration projects, which entail large degrees of risk and uncertainty, multiple and changing objectives, and phased components" (NRC, 2004). Given the size of the Missouri River and its basin, the many states it covers, the complexities of river ecology and the life cycles of endangered species, and the many institutions and stakeholders involved, it is reasonable to acknowledge these challenges and uncertainties and proceed with a conscious effort to continuously learn from the results of management actions and adjust them as necessary. However, adaptive management applications for Missouri River recovery have encountered many of the difficulties in implementing functional adaptive management programs described in this chapter. Without a decision-relevant, science-based management framework, habitat restoration and endangered species programs along the Missouri run the risk of being uncoordinated, chaotic, inefficient, and ineffective.

To date, the Corps of Engineers ESH and SWH projects have been implemented and monitored with only limited strategic guidance and have not been part of a systematic, long-term adaptive management program. The reversal or slowing of declines of endangered and threatened bird and fish species cannot be accomplished immediately. Similarly, management of sediments and nutrients associated with these projects will be an ongoing, long-term process that will be affected and guided by new scientific information,

possible changes in laws and water quality standards, and shifting social preferences regarding Missouri River management and resources.

If a more systematic form of adaptive management is to be developed and applied to Missouri River ecosystem, sediment, and related resources management, it will entail more than development of appropriate guidance documents. At a minimum, it will require a sustained commitment of resources for monitoring and science programs, stakeholder participation and discussions, expert input and advice, and patience in working with large ecological systems and species that do not respond quickly or predictably to management actions.

If federal agencies and others are to implement a more structured adaptive approach to habitat and broader ecosystem restoration and to other currently authorized and future authorized purposes, those efforts will be more effective if they are founded on science-based evaluation, including uncertainties and outcomes of interventions like ESH and SWH projects and their effects on endangered species and river ecology. This report's recommendations for strengthening these programs—all of which should contribute to a more science-based and adaptive approach to Missouri River ecosystem management—are:

Develop performance objectives that are based on ecological and biological variables and designed to determine if compliance actions are reducing jeopardy to listed species.

The development of metrics more closely linked to life cycles of endangered species will complement the 'acres created' metric and should help more clearly determine the extent of habitat mitigation project success.

Develop conceptual ecological models (CEM) for the three endangered species that will consider and evaluate all variables that affect reproduction and survival.

Development and refinement of these types of models will allow for testing of multiple hypotheses regarding environmental variables and their influences on species life cycles, recruitment, and regeneration.

Ensure that ecosystem monitoring is targeted to testing of hypotheses derived from the conceptual models, and that findings are used to further refine the models and gauge progress toward attaining management goals.

Monitoring to date has been extensive and can form a good platform for future evaluation. There will, however, have to be a stronger link between monitoring and answers that are needed for effective adaptive management, both to improve the habitat creation programs and to understand trends in populations of terns, plovers, and sturgeon.

Explicitly assess progress of relevant MRRP programs towards achieving the 2000/03 Biological Opinion goal of reducing jeopardy to the three listed species.

Corps management strategies to address sediment and nutrient issues in the Missouri River are undertaken through multiple interdependent programs within the MRRP under their Biological Opinion compliance responsibilities as directed by the U.S. Fish and Wildlife Service reasonable and prudent alternatives. The adequacy of sediment management and restoration actions like creation of ESH and SWH, therefore, depends on an effective and efficient MRRP informing the FWS, and the FWS responding to new knowledge gained. An essential element for successful adaptive management is that management actions are reviewed frequently based on monitoring and assessment programs, and that management alternatives are revisited and modified as needed. An effective adaptive management process requires confirming that existing management actions directed by the Biological Opinion and implemented through the MRRP are necessary, sufficient, and appropriate for contributing to species recovery, or whether MRRP program elements or Biological Opinion reasonable and prudent alternatives need to be adjusted based on evaluation of results and what was learned.

This chapter has discussed Corps of Engineers ESH and SWH projects that are being implemented along the lower Missouri River in compliance with directives from the Biological Opinion. The ultimate outcomes of these site-level projects, and whether they will result in jeopardy status being removed for endangered bird and fish species, is not known—nor will it be known for years. Adaptive management principles dictate that, in addition to these ongoing projects, consideration be given to alternatives that might be implemented if ESH and SWH project objectives are not or cannot be achieved as originally planned. Further, beyond requirements specified in the Biological Opinion, there are several new, major system-wide studies and initiatives such as the Missouri River Ecosystem Restoration Plan (MRERP), the Missouri River Recovery Implementation Committee (MRRIC), and the Missouri River Authorized Purposes Study (MRAPS). These new initiatives consider not only ongoing projects for endangered species recovery, but also management actions at a system-wide scale that can address a fuller array of restoration options and authorized system uses.

Given the uncertainties associated with outcomes from Corps of Engineers Emergent Sandbar Habitat and Shallow Water Habitat programs, it is possible that they may not meet requirements of the Biological Opinion to avoid jeopardizing the continued existence of the tern, plover, and sturgeon. The ESH and SWH programs, and the suite of new Missouri River system initiatives and studies, thus should formulate alternative actions that eventually may need to be implemented to increase the likelihood of species recovery.

5
Sediment Management Alternatives and Opportunities

The Corps of Engineers Missouri River emergent sandbar and shallow water habitat construction programs described in Chapter 4 include excavation and disposal of sediment within and near the Missouri River's main channel. Other sediment management activities have also been proposed, some of which are being implemented locally, but not yet extensively along the river. In addition, questions have been raised recently about the potential for sediment management along the Missouri to affect coastal wetlands and marine water quality as far away as the Mississippi delta of Louisiana and the hypoxic zone in the northern Gulf of Mexico.

Some of the proposed sediment management activities are technically feasible, while others are more complex, uncertain, expensive, and as yet are subjects only of preliminary discussion and analysis. Manipulation of sediment along a river which has already been significantly engineered (Chapter 2) raises many questions about intended or unintended consequences, effectiveness, and time scales of expectable responses.

This chapter explores the primary alternatives for reintroducing sediment into the Missouri River. Specifically, the chapter answers, but is not limited to, the following questions in the Statement of Task:

Question 6: Are there alternatives for reintroducing sediment into the system? What are they and what are the key constraints surrounding these alternatives?

Question 3: What is the significance of Missouri River sediments to the restoration of Louisiana's coastal wetlands?

The alternatives explored most extensively in the chapter include: habitat construction, removal of riverbank control structures, limitations on commercial dredging, bypassing of sediment around mainstem dams, dam removal, and increasing sediment deliveries from tributaries. All of the discussions are exploratory and aimed at definition of the problem and its implications. None of the discussions should be construed as recommendations for or against any course of action. Decisions about particular actions would require more extensive analysis and will depend on future development of economic, engineering, and environmental conditions along the Missouri River.

MISSOURI RIVER SEDIMENT RE-INTRODUCTION ALTERNATIVES

Emergent Sandbar and Shallow Water Habitat Projects

The Corps' Emergent Sandbar Habitat and Shallow Water Habitat projects have implications for sediment loadings and transport and therefore for channel morphology and habitat maintenance. Sediment in transient storage during its passage along the river channels and floodplains of the Missouri River valley has value for habitat formation and has both positive and negative influences on infrastructure. As discussed in Chapter 2, these implications are in addition to the direct ecological dimensions of the projects described in Chapter 4.

The Corps of Engineers currently is constructing emergent sandbar habitat in the approximately 40 miles of river channel between Gavins Point Dam and Ponca State Park (see Figure 4-1). The bed of the Missouri River in this reach has been degraded (scoured deeper) by as much as 12 feet since dam closure (Jacobson et al., 2009). Sandbars in this reach of the river usually are constructed from sand dredged from the channel bed, and therefore likely to consist largely of relatively coarse, slow-moving bedload sand. The constructed bars gradually erode, however, and their sand is re-distributed to the bed with no net effect on the river's sediment balance. These sandbars need to be replenished every few years.

The Corps also is constructing shallow water habitat in and along the lower Missouri River channel downstream of Ponca State Park (Figure 4-1). At some sites, chute and backwater channels are excavated in the floodplain (sometimes taking advantage of former natural chutes) and the sediment is returned to the main channel. The sediments are fed into higher velocity areas of the river and thus are thus disperse downstream. An associated strategy involves excavating sediment to depths of several feet along the margins of the main channel and building structures to slow the flow along some channel margins. Material from the main-channel margin is likely to be coarser than sediment from chute excavations. Because of the stratified nature of typical floodplain sediments, it may be possible to separate excavated material dominated by chemically active clays and silts from more inert sandy deposits, and then selectively return only the sandy deposits to the channel.

A 2009 report authored by U.S. Geological Survey and Corps of Engineers professional staff contains the most valuable dataset available for a quantitative assessment of the impacts of this practice on the sediment budget and water quality (Jacobson et al., 2009). That report describes how, according to current habitat construction plans, approximately 15,000 acres of land that accumulated in the decades following Bank Stabilization and Navigation Project implementation would be excavated and approximately 34 million tons (MT)/year of sediment would be returned to the channel in each of 15 years. This would amount to an increase of about 60 percent of the current annual sediment load passing Hermann, Missouri.

Measurements of grain-size distributions of excavated material at sampling sites at Jameson Island (Figure 5-1) indicate that if the excavated spoil is transported quickly through the narrowed and leveed mainstem channel (which is designed to keep the sediment in motion), the sand load passing Hermann would be almost tripled—from 14 to 40 MT/yr—and the silt-clay load would be increased by about 20 percent, from 41 to 49 MT/yr (Jacobson et al., 2009). The silt-clay would travel as washload, enhancing turbidity and traveling rapidly downstream with

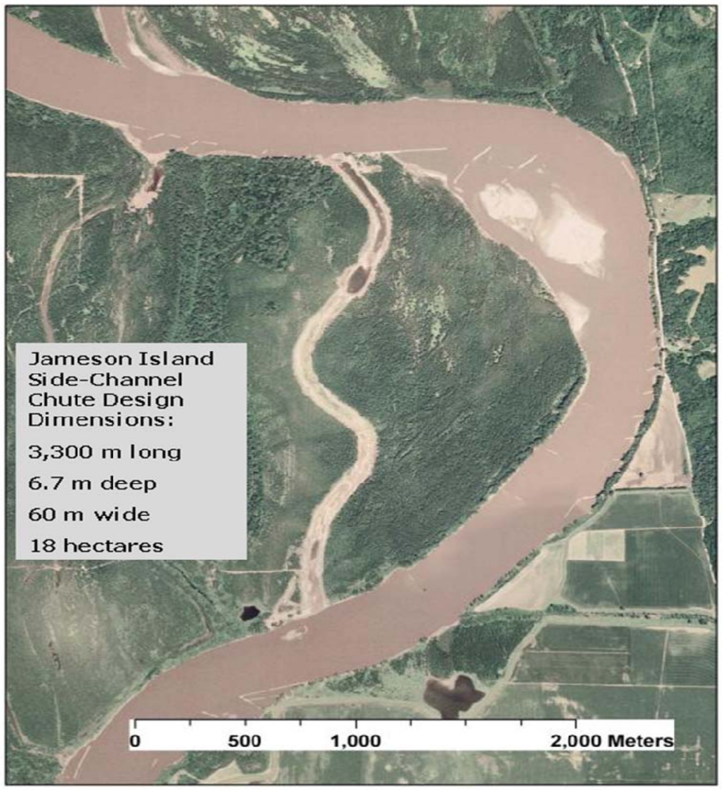

Figure 5-1 Aerial view of Jameson Island chute. Jameson Island data were used as the basis of the overall sediment load estimation presented in this chapter, and on discussion of changes in the river's phosphorus load (presented in Chapter 6).
SOURCE: Jacobson, 2010, personal communication. Provided by Robert Jacobson, U.S. Geological Survey.

only small amounts being trapped in off-channel shallow water habitats. The sand, having formerly entered the floodplain mainly as suspendible bed-material load (Chapter 2), would be flushed downstream and dispersed as transient additions to bars and floodplains along the lower Missouri River. Some of the sand excavated from the floodplain would be coarse enough to travel as slowly moving bedload, but this component is likely to be small, especially in the reach upstream of the Platte River where the bed has degraded by as much as 12 feet since dam closure.

Downstream of the confluence with the Platte River, Missouri River bed degradation is locally variable or absent (Jacobson et al., 2009), and an increased sand load of the magnitude proposed under full project implementation requires careful consideration of its potential for causing some bed elevation, bar building, and complications for navigation. The problem could be assessed in greater detail through of a detailed modeling study, utilizing measured grain-size distributions and channel morphology, of the probable impact of the temporary sand storage on potential cross-section changes. Existing data for the river could be used for such an assessment, and model results could be evaluated with high-value monitoring resources that also exist within relevant federal agencies. Such a study also would allow consideration of lengthening the habitat construction period if the capacity of the channel was inadequate to pass the sand without bed-elevation changes.

Removing Bank Stabilization Structures

Downstream of Sioux City, Iowa, the Missouri River is channelized and controlled by levees, revetments, jetties, wing dikes, and other river training and control structures of the BSNP (USACE, 2009b). These structures make it difficult to establish and maintain complex channel and floodplain habitats that depend on the temporary storage and frequent alteration of sediment accumulations in the form of channel bars and off-channel water bodies. The control structures are designed to maintain a narrower and more rapid flow that scours a deeper and less complex channel. The degree to which economic activity, transportation, and public safety along the Missouri valley depend on these control structures makes it unlikely that the river ever will be extensively released from these constraints. However, the purchase by the Corps of Engineers of some leveed, but still flood-prone, land along the Missouri River raises the possibility that over coming decades some of these river control works may be breached in rural reaches, either naturally or by design. Lands acquired through September 2009 under the Missouri River Mitigation Program total 56,606 acres, which amounts to 34 percent of the 166,750 acres authorized for purchase (Bell and Bitner, 2010). Large areas of other flood-prone land are protected by non-federal levees that are aging and that place maintenance burdens on local levee districts.

The river will migrate laterally if revetments are not maintained. In some reaches, such migration would undermine sediment that was stored during the era of bank stabilization, causing a net increase—or more exactly a partial restoration—of the river's sediment load. If so, the general effects on sediment transport, sedimentation, and water quality would be similar to those discussed above for chute excavation. The magnitude and location of individual impacts of this kind are beyond the scope of this report, but could be more carefully evaluated with greater precision for planning purposes if resources were applied to the problem. Since such a program of releasing the river from its lateral constraints would happen gradually over many decades, and be accompanied by both sediment removal from the floodplain and sequestration of sediment on the floodplain, the net effect on the downstream annual sediment flux would not be a large percentage change. Over coming decades, however, the sediment locked in storage by Bank Stabilization and Navigation Project structures would be released gradually back into the river.

It is not likely that reconfiguring the navigation channel will be either desirable or acceptable to the many communities, farms, and other parties along the Missouri River in the near future. These parties have legitimate concerns about the potential impacts of channel reconfiguration (e.g., widening of the channel for the purpose of creating extensive shallow-water habitat and sandbars within and along the margins of the channel) or changes in river bed elevation. These changes could affect erosion and flooding, with consequent impacts on homes, infrastructure (transportation, telecommunications, power), farmland, and other floodplain property. At some point in the future, changes in technology or economics may decrease the importance of maintaining a large, viable channel for commercial navigation. At that time, the potential might become more attractive for freeing the channel to migrate within suitable public lands or private lands with flood easements and for increasing the width of the active floodplain subject to regular inundation.

In the interest of reviewing all potential consequences of channel widening to the extent possible, reestablishing some of the river's wide, shallow, braided channel characteristics in any of the river's reaches would benefit river ecology by allowing more space and more natural sediment storage and transmission processes for the creation of shallow-water and emergent-sandbar habitat. A number of previous studies have documented the potential benefits of restoration of some of the pre-historic inundation and alluvial processes (Galat et al., 1998; NRC, 2002; Opperman et al., 2009). Creating habitat in the vicinity of the present navigation channel is difficult because the narrow channel inhibits the sediment accumulation needed for the creation of sandbars. It is also difficult to make river-wide generalizations about the magnitude and sustainability of simultaneously maintaining navigation and reconfiguring the channel for ecological benefits without a thorough, reach-by-reach assessment and modeling study.

Smaller programs of levee setback and opening of secondary channels have been executed on large alluvial rivers in Europe, including the lower Rhine (Buisje et al., 2002), the Danube (Schiemer at al., 1999), the Loire (Belleudy, 2000), and the Rhone (Amoros, 2001). Predicting the impacts of major channel reconfiguration in the Missouri is difficult, because no similar projects have been attempted there. There are no river restoration projects in the United States that have removed channel controls on the scale of the Missouri River, and such a program would have to evolve gradually in the context of regional development so as to minimize possible impacts and disruptions to other sectors.

Several more limited and local strategies, applied singly or in combination, could be used to move the channel toward a more complex and dynamic configuration, with more secondary channels, sandbars, and shallow water habitat: Removal of revetments and removal or reshaping of dikes would allow the river to erode its banks, resulting in widening of the channel. Assuming that sediment was available (which in the short term is likely to be true only downstream of the Platte River confluence), this process would likely lead to re-establishment of sand bars and development of shallow-water habitat at the margins of the main channel, as has been observed in side channels without revetments (Jacobson et al., 2004). Levees could be set back, or aging levees could be allowed to fail naturally, to allow floodwater access to portions of the floodplain and the river to reoccupy and scour out some inactive side channels during particularly high flows. Riverside sites with major infrastructure investments, such as settlement, transportation, water supply and power plants, would continue to require protection with existing or enhanced revetments and levees. The Corps has been experimenting with local projects to notch and otherwise modify dikes since the 1970s. Given current uncertainties, the process of gradual channel reconfiguration on a local scale could continue and be conducted as part of an adaptive management strategy. That is, appropriate monitoring could be used to support additional fluvial geomorpohology modeling and hypothesis testing, broaden the options explored, and anticipate likely outcomes based on interpretations of floodplain sedimentology, river channel mechanics, and ecological linkages.

Commercial Dredging

The lower Missouri River has been dredged since the nineteenth century to permit navigation. Since completion of the 9-foot channel and following closure of the dams upstream in the early 1960s, much less dredging has been required. During the last several decades, however, volumes of commercial dredging on the mainstem and its tributaries increased from approximately 1.3 MT/yr in 1974 to 8 MT/yr in 2006 (USACE, 2008). Most commercial dredging on the mainstem is concentrated near the larger urban centers, particularly Kansas City. Dredging in the Missouri River's tributaries is not well quantified. However, roughly 1.4 MT/yr of sand are dredged from the lower Kansas River, contributing to bed degradation and related infrastructure problems (e.g., degradation of soil under bridge foundations) in the lower Missouri River (Rasmussen et al., 2005). Dredging and removal of sandy bed material load from the major tributaries contribute directly to reduced sediment loads in the mainstem Missouri River and at points downstream. In principle at least, reducing sand dredging from the reach downstream of the main right-bank tributaries will ameliorate channel-bed degradation in the Missouri River near Kansas City.

It is estimated that commercial dredging between 2003 and 2005 removed an amount equivalent to about 40 percent of the sand flux during the same period past Hermann, Missouri (Jacobson et al., 2009). However, quantification of the likely impact on bed elevation requires a model-based estimate of bed-material transport and storage. Given the simplicity of the channel and the amount of existing data on sediment characteristics, hydraulics, and channel geometry within the lower Missouri River, such an analysis would be quite straightforward.

Bypassing Sediment Around Mainstem Dams

Bypassing of sediment around major dams has been suggested as a means of ameliorating some of the undesirable effects of the massive reduction of sediment flux down the Missouri River since the 1930s. The potential for substantial sediment releases from these dams would depend on: (1) volumes and grain sizes of sediment that can be mobilized, (2) the rate at which each grain-size component could travel downstream, and (3) the degree to which each grain-size fraction would be stored in the floodplain along the Missouri and Mississippi rivers.

The most important and implacable of these constraints lies in the fact that most of the sediment that has been stored behind dams in the Missouri and its tributary basins is far upstream of any direct connection to the Mississippi and even to the lower Missouri River. This discussion thus focuses on the lowermost dam, Gavins Point, because if bypassing of sediment is to become feasible, it is most available at this most downstream impoundment. It must be emphasized, however, that all experience with sediment bypassing has been accumulated on dams much smaller than those on the Missouri, and investigations of what is possible for large dams remains within the realm of mathematical modeling.

There are two fundamental strategies for moving sediment past reservoirs and dams: capturing and diverting sediment before it deposits in the reservoir, or re-mobilizing sediment that has accumulated within the reservoir. The first involves constructing a canal or pipeline to collect and convey sediment over the dam or through low-level outlet works; this is the only option in very large reservoirs. Sediment bypassing opportunities have been designed into Chinese dams at Three Gorges on the Yangtze River and at Xiaolangdi on the Yellow River; and they have been retrofitted into the rock wall of the canyon at the older Sanmenxia dam on the Yellow River. The general principle behind the design of these works is to open the dam flow control structures when sediment-rich flows are expected and allow the river to flow freely through the reservoir and bypassing works. The effectiveness of their operations has not yet been widely documented or analyzed. An alternative is remobilization of already-deposited sediment in the reservoir and moving it past the dam using flushing, sluicing, or hydraulic/hydrosuction dredging, and discharging it into the river downstream.

Sediment flushing is conducted by draining the reservoir through low-level outlets and allowing river-like conditions to be established throughout the sediment deposits. The increased water velocity mobilizes deposited sediment and moves it downstream. Flushing is practiced worldwide and guidelines for its implementation have been published (e.g. White et al., 2000). The method is performed in two reservoirs within the Missouri River basin: Guernsey Reservoir on the North Platte River, and Spencer Dam on the Niobrara River. Sediment sluicing is similar to flushing except that the reservoir is only partially drawn down during the operation, leaving some water storage available upstream. The increased water velocities and tractive forces mobilize only sediment deposited near the dam. Hydraulic and hydrosuction dredging techniques transport sediment-laden water via pipeline from the reservoir to the downstream river. Hydraulic dredging requires an externally powered pump, while hydrosuction dredging uses the suction pressure generated by the elevation differences between the up- and downstream water levels to drive the sediment and water into the pipeline (Hotchkiss and Huang, 1995).

The decision on the most appropriate method for moving sediment past a dam and making the dam and its reservoir sediment neutral for the river depends on economic analyses of costs and benefits, the acceptability of the method and its results to stakeholders, and on laws and institutional agreements for Missouri River operations. It might also include relief from negative impacts in the reservoir itself, such as the reduction of operating efficiency and the raising of riparian ground water levels around the accumulating wedges of sediment. The physical factors that influence the decision are largely the size of the reservoir with respect to the amount of entering sediment and the size of the reservoir with respect to the throughflow of water (Coker et al., 2009). A reservoir that is small with respect to the amount of sediment and water flowing into it may be a reasonable candidate for sediment flushing whereas a reservoir that is large in comparison to its sediment and water inflows may be better managed through sluicing.

Gavins Point Dam and its reservoir, Lewis and Clark Lake, represent an example of a system where flushing is likely to be the best solution for moving sediment past the dam (Coker et al., 2009). Lewis and Clark Lake is relatively small in comparison to the water and sediment that enter its upstream areas, and draining the reservoir through low-level outlets would likely hasten the movement of sediment from the lake to downstream areas. Some of the sediments entering Lewis and Clark Lake from the Niobrara River have already been flushed through a reservoir at Spencer Dam.

It has been estimated that only about 6 MT/yr of sediment currently accumulate in the lowermost reservoir behind Gavins Point Dam (Coker et al., 2009). That estimate envisioned the eventual (50 years from now) passing of sediment around Gavins Point Dam at the rate of 6 MT/yr. Most of the sandy sediment entering this reservoir is stored at the upstream end of the Niobrara River delta in Lewis and Clark Lake. There are severe constraints on bypassing coarse sandy sediment, and one proposed bypassing strategy envisions using much of the current stored sand to raise the elevation of the tributary deltas rather than bypassing it around the dam (Coker et al., 2009). In the same report, it was estimated that 60 percent of the released sediment would be silt and clay and approximately 25 percent of the sand would be fine enough to behave as washload through the degraded reach (estimated from figures in Coker et al., 2009). Therefore this action will result in little if any sediment settling to the bed of the lower Missouri River below the dam to ameliorate the bed degradation.

Almost all the bypassed sediment would be flushed quickly downstream, with the bed-material sand participating in transient storage bars within and along the margins of the channel. This bar-building material is likely to reside for longer in the 200-km-long reach between the vicinity of Omaha and St. Joseph that has been highlighted as “stable-aggrading” (Jacobson et al., 2009; Figure 8). Some of the sediment would be expected to become deposited behind the increasing number of bank structures that are being installed for shallow water habitat (see Chapter 4). The engineering activities that maintain the self-scouring navigation channel are likely to ensure the mobility of this relatively fine sediment supply from the reservoir.

The enhanced washload would be flushed downstream efficiently in the leveed and simplified channel of the lower Missouri River. A small fraction of it would be stored in the floodplain in diffuse and channelized overbank flows, but even if the entire 6 MT/yr that might bypass Gavins Point dam were to reach St. Louis, it would constitute only a roughly 10 percent increase in the total sediment flux into the Mississippi from the Missouri. This amount is considerably smaller than the 34 MT/yr expected to be returned to the river by Corps projects for shallow water habitat, although at this point the habitat construction projects are slated to be conducted over a 15-year period.

Dam Removal

Gavins Point Dam has been considered by some interest groups for removal to restore the downstream sediment supply. Although dam removal has been used to promote river restoration on some U.S. rivers, and more than 700 dams have already been removed, they have all been small (less than 30 feet high). The largest U.S. dams slated for demolition are Glines Canyon and Elwha dams on the Elwha River in Washington, which have a combined reservoir storage capacity of 48,000 acre-feet. By comparison, the storage capacity of Lewis and Clark Lake (impounded by Gavins Point Dam) is 492,000 acre-feet. There are no precedents for the removal of such a large structure, and if it were to be removed the augmentation of the sediment supply would again be only about 6MT/yr (Coker et al., 2009), although the coarser sandy deposits at the upper end of the Niobrara River delta would eventually be washed downstream under this strategy. Only removal of all or most of the dams on the mainstem and tributaries would restore the sediment supply to the Missouri River at Yankton approximately to pre-regulation quantities. Only restoration of the coarsest bedload fraction of the river's load would supply sediment that could remain for long on the bed of the degraded reach upstream of the Platte River; this generalization could be refined by totaling the volumes stored in successively further upstream dams. Restoration of even approximately natural sediment loading would require the unlikely (most energetically demanding) remobilization of the coarse fraction of the sediment input to each reservoir, which is deposited in deltas and fans at the upstream ends of the reservoirs and in the delta and lowermost reaches of tributaries such as the Niobrara River.

Increasing Sediment Deliveries from Tributaries

Before the 1950s, tributaries supplied more than 175 MT/yr of sediment to the Lower Missouri River, and even today when they are extensively impounded, they supply almost all of the 55 MT/yr that passes Hermann, MO (see discussion in Chapter 2). Sediment contributions vary between the diverse reaches within the major tributary basins because of the variety of their geology, soils, topography, and land use. Small tributaries on the left bank (east or north side) that drain loess areas contribute mostly fine grained sediment that passes through the system without settling on the channel bed. The west-side tributaries contribute more sand. The Niobrara River contributes a relatively large sand load to Lewis and Clark Lake because its watershed is primarily the Sand Hills region of Nebraska. Substantially increased contributions of sediment from tributaries to the Missouri River downstream from Gavins Point Dam are unlikely under present sediment management because these rivers have large storage reservoirs of their own. Eighteen reservoirs control flow from 85 percent of the Kansas River basin (Perry, 1994), and two large impoundments (Harry S Truman Reservoir and Lake of the Ozarks) control most of the flow of the Osage River.

With regard to prospects for bypassing sediment around dams on the Missouri's right bank tributaries, some sediment is already flushed around the Guernsey and Spencer dams on the North Platte and Niobrara rivers. Increased sediment bypassing of dams might aggravate flooding levels in the lower reaches of some tributaries, depending whether the bypassed sediment were washload, suspendible bed material or bedload. The fact that these tributaries already supply more sediment to the lower Missouri River than could be supplied at steady state from Lewis and Clark Lake suggests that this source may be worth assessing in the future if additional options for reintroducing sediment to the Missouri are pursued.

MISSOURI RIVER SEDIMENT MANAGEMENT AND LOUISIANA WETLAND BUILDING

Since closure of the Missouri River mainstem dams and the construction of bank stabilization projects under the BSNP, Louisiana's coastal wetlands have experienced substantial erosion and losses. Louisiana has lost 1,900 square miles of coastal wetlands since the 1930s (Barras et al., 2003). Between 1990 and 2000, wetland loss was approximately 24 square miles per year and the projected loss over the next 50 years (and accounting for current restoration actions) is estimated to be approximately 500 square miles (Barras et al., 2003). These losses are of concern for several reasons, and the Corps of Engineers and State of Louisiana have conducted many studies and initiatives aimed at coastal protection and restoration. Given the historically important role of the Missouri River in delivering sediments to Louisiana, there is a strong perception that reductions in these sediment deliveries have been an important factor in wetlands losses. Some observers have suggested it might be possible to engineer an increase in the supply of Missouri River sediment to the threatened wetlands of the delta (Barry, 2008; Schleifstein, 2010). Others (e.g., Allison and Meselhe, 2010; Kim et al., 2009) have considered how sediment from the Mississippi River might be diverted out of the channel to reconstruct at least part of the coastal wetlands, even if there is no prospect of restoring their original extent with the available sediment supply (Blum and Roberts, 2009).

In addition to reduced sediment deliveries from the Missouri and Mississippi rivers, wetlands losses have been affected by a complex combination of other factors (see also NRC, 2009):

- Crustal downwarping;
- Sea level rise;
- Natural consolidation of soils;
- Reduced sediment delivery from the Mississippi River because of stabilization of the river banks;
- Construction of flood control structures along the mainstem Mississippi River in Louisiana that prevent flooding of wetland by sediment-laden waters and conveyance of river sediments to the delta front and over the edge of the continental shelf;
- Wetland edge erosion by storms that are likely exacerbated by the larger open water fetch in ever-enlarging distributary bays (e.g., Atchafalaya and Barataria);
- Navigation and pipeline canals cut through the wetlands by the oil and gas industry;
- Offshore disposal of dredged materials by the Corps of Engineers.

Missouri River sediment clearly was important in contributing to maintenance of the elevation of Louisiana coastal wetlands. Given the many factors that have affected losses of these wetlands, however, the relative importance of reduced sediment deliveries to Louisiana remains difficult to quantify (Turner, 1997).

It is inconceivable that increases in the supply of Missouri River sediment from any strategy described in this chapter could re-establish a near-natural rate and volume of sediment delivered to the Mississippi River delta. As noted earlier in this chapter, full establishment of the Corps' shallow water habitat program, and disposal of all of the excavated sediment into the channel and its complete transfer to the delta (unlikely because some of the suspendible sand is likely to be incorporated into the floodplain of the Mississippi River) would increase the sediment supply past Hermann, Missouri by roughly 60 percent—or an additional 23 percent of sediment supply to the head of the delta—for at least 15 years (Jacobson et al., 2009).

If the SWH program was terminated, and then sediment was to be flushed past Gavins Point Dam, the sediment load past Hermann, Missouri would increase by only 10 percent—roughly 4 percent of the load delivered to the head of the Mississippi delta. These values are maxima because the sand supply would be diminished by being incorporated into bars and the floodplain, and a portion of the washload could be lost to the vegetated floodplain.

Approximately 3.6 MT/yr of sand are dredged from the bed of the middle Mississippi River between the Missouri and Ohio River confluences, and the Mississippi River main channel in that stretch is narrow and meandering, with scattered chutes and backwater channels (Pinter et al., 2004). Most of this sand was dredged from flow divides, tributary mouths, and thalweg crossings. The fate of the dredged material is difficult to predict if it was returned within the channel margins, but it is likely to become involved in the floodplain during some part of its downstream transit. However, the dredged reach does not seem to offer much opportunity for the long-term storage of washload.

The lowermost 155 miles of the Mississippi channel have been held in place by dikes, with only limited accretion and erosion occurring along bank lines inside the artificial levees, and ephemeral muds are temporarily deposited from suspension in water depths less than 60 feet along bank areas during low water (Nittrouer et al., 2008). Downstream of Baton Rouge, Louisiana (River Mile 230), the Mississippi River channel flows on local cohesive sedimentary formations with no long-term accumulation of sediment on its bed. Transient sediment on the bed is in the fine-to-medium sand range. Thus, although loss to overbank deposition would likely involve a large fraction of the washload in a natural river (e.g. Dunne et al., 1998), the levees.along the Mississippi River increase the likelihood that most of the flow and its washload will stay in the channel.

Any significant increase in the quantities of sediment released from storage in the Missouri River mainstem reservoirs upstream of Lewis and Clark Lake would require remobilization of the silts and clays stored far upriver behind Fort Randall, Big Bend, Oahe, and Garrison Dams. These reservoirs—Lake Francis Case, Lake Sharpe, Lake Oahe, and Lake Sakakawea—were recipients of fine-grained sediments that were washed abundantly from the soils developed on the Mesozoic shales of North and South Dakota. Because of their small grain size, these materials, once suspended, would be mobile as washload. Their greater distances upriver, however, and the necessity of their having to be bypassed through more than one reservoir and around the dams, would require extensive, expensive efforts in both planning and implementation.

SUMMARY

The Corps of Engineers is implementing Emergent Sandbar Habitat and Shallow Water Habitat projects along the Missouri River consistent with the 2000/03 Biological Opinion Reasonable and Prudent Alternative. These projects aim to restore a portion of some features of the pre-regulation Missouri River to help protect endangered bird and fish species. As described in Chapter 2, prominent features of the pre-regulation mainstem Missouri River were a high sediment load traveling in suspension and along its bed and highly turbid conditions.

These Emergent Sandbar Habitat and Shallow Water Habitat projects are reintroducing some sediment into the Missouri River, and are gradually reintroducing channel mobility and hydraulic connections between the main channel and its floodplain that support new habitat formation. This chapter discusses several other alternatives that might be employed to re-introduce additional sediments into the Missouri River. This chapter describes and comments on sediment management alternatives independent of one another, and does not consider how different combinations of these alternatives might affect the sediment regime in the river or beyond the mouth of the river. Implementing combinations of these alternatives would require current Missouri River planning efforts (MRERP and MRAPS; see Chapter 3) to formulate and evaluate combinations of the actions discussed in this chapter, as well as other actions, at different scales and locations.

Primary alternatives that might be employed to re-introduce additional sediment into the Missouri River are: removing bank stabilization and control structures; commercial dredging; bypassing sediment around mainstem dams; dam removal; and increasing sediment from tributaries.

Implementation of any of these alternatives would be constrained by financial, technical, and other factors. A major constraint on any alternative is the degree to which current economic activities, transportation infrastructure, and public safety depend on the existing system of dams and river bank control structures. It is not likely that major reconfiguration of the river channel, or removal of a large dam, would be desirable or acceptable to a large majority of Missouri River valley residents in the near future.

Bypassing of large amounts of sediment around Gavins Point Dams may be technically feasible. This option, however, would be expensive and have little potential to significantly re-establish pre-regulation supplies of sediment that were delivered to Louisiana. Substantially increased contributions of sediment from tributaries to the Missouri River downstream from Gavins Point Dam are unlikely under present sediment management rules because these rivers have their own large storage reservoirs.

There has been a renewed interest in the prospects for increasing the amounts of sediment transported downstream by the Missouri River and delivered to Louisiana. However, there is little potential in the near future for any strategy described in this chapter to re-establish volumes of downstream sediment delivery that approach pre-regulation volumes delivered to Louisiana. The Corps of Engineers Missouri River habitat construction projects could release enough sediment to increase the supply to the Mississippi delta by 10-20 percent for at least the next 15 years (depending on the trapping efficiency of the Mississippi floodplain). Remobilization of sediment in Lewis and Clark Lake would at best increase the supply of wetland constructing sediment to the Mississippi delta by only a few percent. Other prospects for mobilizing sediment in the Missouri and its tributaries are not only difficult to conceive of for the near future, but they are more likely to have local effects on bar building and local channel mobility and complexity than to contribute significantly to wetland construction in the Mississippi delta.

The amounts of sediment likely to be available for transport from the Missouri River to the Mississippi River delta are smaller than the quantities that made the journey before the construction of mainstem dams and implementation of the major bank stabilization structures.

6
Water Quality and Missouri River Sediment Management

This report has documented how the bank control structures of the BSNP, the dams of the Pick-Sloan Plan, and water projects on Missouri River tributaries, have transformed hydrologic and sedimentary processes in the Missouri River. As explained in detail in Chapter 2, these structures have trapped and immobilized large volumes of sediment in the river's floodplains and behind mainstem dams, greatly reducing sediment concentrations in and volumes of sediment transported by the post-regulation Missouri River. These changes have had many consequences, one of which was compromising the natural habitat of some of the river's native bird, fish, and plant species. As explained in Chapter 4, the federal 2000/03 Biological Opinion issued under the Endangered Species Act has directed ways in which some portion of the river's pre-regulation sediment regime and other conditions can be restored to improve prospects for federally-listed fish (pallid sturgeon) and birds (least tern and piping plover). In Chapter 5, other alternatives for sediment management on the river were described at a general level, with the caveat that further understanding of their technical and socio economic viability would be required as MRRP, MRAPS and other programs develop over time.

The statement of task to this committee also reflected concerns that sediment introduction, with associated phosphorus, may have detrimental effects on water quality within the river and as far away as the northern Gulf of Mexico. As described through this report, high concentrations of sediment were a natural feature of the pre-regulation river and important to its native species, and also important to land-building processes in parts of the Mississippi River delta. At the same time, in many settings and river systems across the country, sediment is recognized as a pollutant, with significant federal and state program efforts in place to keep sediment out of streams, rivers, and lakes. Therefore, in considering actions to reintroduce sediment to the Missouri River, it is important to recognize the historic sediment volumes, sources and characteristics when defining water quality criteria and regulations for the Missouri River watershed.

In considering the full range of implications of the Corps of Engineers habitat projects along the Missouri River, it is therefore important to understand not only provisions of the Endangered Species Act, but also provisions of the Clean Water Act—especially setting water quality standards for sediment and phosphorus concentrations.

This chapter responds to two questions in this report's statement of task:

- *What is the significance of the Missouri River sediments to the Gulf of Mexico Hypoxia problem?* (question 2), and
- *What are the key environmental and economic considerations regarding nutrient loads and/or contaminants in Missouri River sediment? To what extent can such issues be addressed with management strategies?* (question 4)

The first section of this chapter discusses potential effects of enhanced Missouri River sediment transport and associated phosphorus loads on hypoxia in the Gulf of Mexico. The following sections focus on setting water quality criteria for sediments and nutrients that will be protective of designated uses. The historical sediment and phosphorus loads in the basin and prior to the construction of the Pick-Sloan mainstem dams are discussed as context for the setting nutrient (phosphorus) and sediment criteria as required by the Clean Water Act. The discussion provides a logic for setting of such criteria in ways that meet the requirements of the Clean Water Act and that can be compatible with ongoing and possible future Missouri River sediment management activities dictated in part by the Endangered Species Act. The chapter concludes with a discussion of the need for improved monitoring of the sediments, nutrients and other chemical constituents in sediments discharged into the river.

POTENTIAL WATER QUALITY EFFECTS IN THE GULF OF MEXICO

Northern Gulf of Mexico Hypoxia

Nitrogen and phosphorus delivered from the Atchafalaya and Mississippi Rivers to the northern Gulf of Mexico combine with conditions of temperature, sunlight, and vertical stratification that are favorable to high rates of photosynthesis and algal growth in the northern Gulf. When these algae, or detritus from their consumers, settle to bottom waters, decomposition of this organic matter consumes dissolved oxygen. Because vertical stratification of the water column creates a barrier between surface and bottom waters, there is little oxygen supply to the bottom layers. Thus, oxygen consumption associated with the decomposing organic matter results in oxygen depletion and concentrations so low that many types of fish and shellfish are unable to survive. This state of low dissolved-oxygen levels (< 2 mg/L) is known as hypoxia.

This northern Gulf of Mexico hypoxic zone ("dead zone" in the popular literature) is a seasonal but perennial feature that covers a portion of the northern Gulf and is roughly the size of Connecticut, New Jersey, and Rhode Island combined (Figure 6-1). This hypoxic zone has been identified as a water quality problem of national significance and decisions about land use and water and sediment management throughout the entire Mississippi basin are now being considered (USEPA, 2001, 2008).

The areal extent of the hypoxic zone has exhibited an increasing trend since the late 1980s and also has displayed significant interannual variability since then (Figure 6-2). Although routine hypoxia monitoring did not start until 1985, modeling and paleo-ecological studies confirm that large-scale hypoxia was not present until the 1970s.

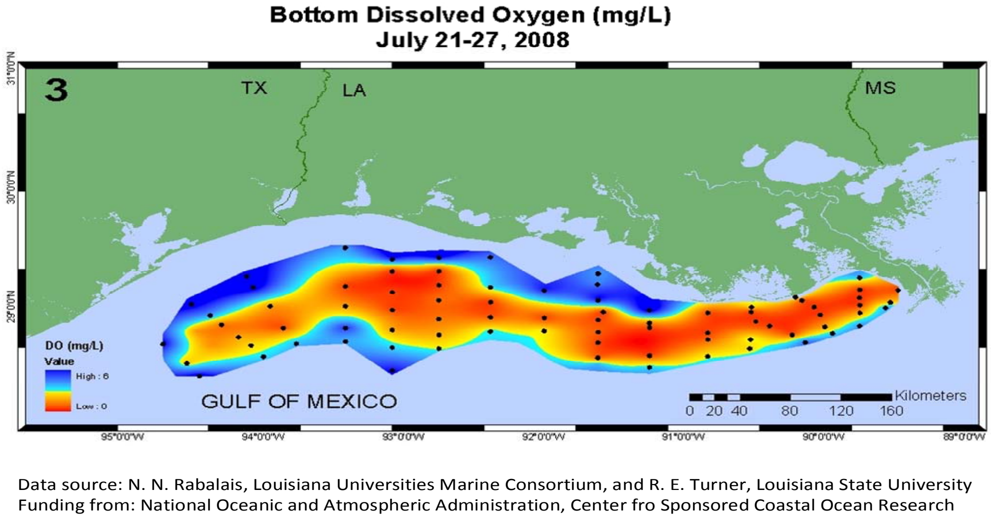

FIGURE 6-1 Bottom dissolved oxygen in Northern Gulf of Mexico.
SOURCE: Reprinted, with permission, from Rabalais and Turner, 2001. © 2001 by American Geophysical Union.

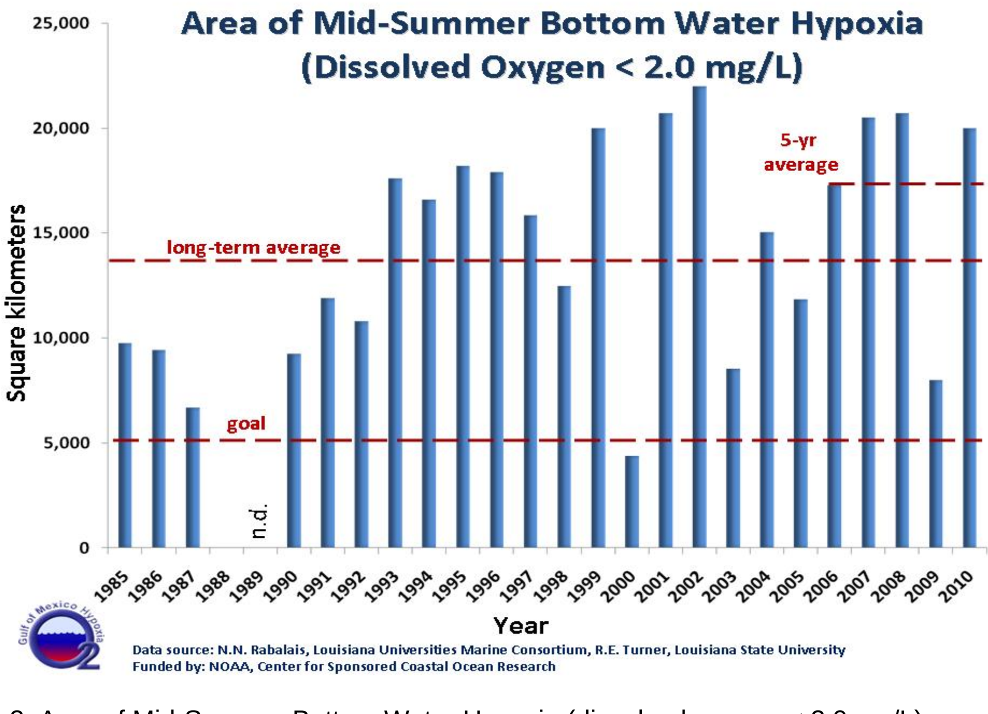

FIGURE 6-2 Area of Mid-Summer Bottom Water Hypoxia (dissolved oxygen < 2.0 mg/L)
SOURCE: Reprinted, with permission, from N.N. Rabalais, Louisiana Universities Marine Consortium.

The zone of hypoxia, and nutrient loadings and water quality across the Mississippi River basin, have been evaluated by many scientists and research teams. Box 6-1 summarizes several recent studies, reports, and initiatives addressing Mississippi River and northern Gulf of Mexico water quality. Box 6-1 does not attempt to provide full coverage of all relevant studies. The reader interested in additional reports and papers on nutrient loadings across the Mississippi River basin, and northern Gulf of Mexico hypoxia may wish to consult the following: (Battaglin, 2006; CENR, 2000; Rabalais and Turner, 2001; Rabalais et al., 2002; Scavia et al., 2003; Scavia and Donnelly, 2007; Turner et al., 2006).

Although excess nitrogen loads are responsible for the long-term increase in hypoxic area, recent reports suggest that phosphorus may also now be contributing to hypoxia, especially near the Mississippi and Atchafalaya river mouths in spring (USEPA, 2007). As a result, federal-led efforts to address the problem have called for simultaneous reduction of nitrogen and phosphorus loads (e.g., USEPA, 2007).

Among several reasons why the northern Gulf hypoxic zone has proven to be a stubborn water quality remediation challenge is that it is affected by factors other than Atchafalaya-Mississippi River nutrient discharges, and that the areal extent varies from year-to-year. These complications make it difficult to precisely track and verify relationships between nutrient loads and the extent of the hypoxic zone. These issues are described in further detail in a subsequent section of this chapter entitled "Measurements of the Hypoxic Zone."

Nutrient Sources

Runoff of nutrients from forests, farms, open fields, urban areas, and discharges of nutrients from industrial facilities and publicly-owned treatment plants across the Mississippi River basin are delivered eventually to the Gulf of Mexico. The largest source of nitrogen and phosphorus in Mississippi River water that is delivered to the Gulf of Mexico is from agriculture (USEPA, 2007; Alexander et al., 2008). Nitrogen loads to the Gulf increased significantly between the mid-1960s and the early 1980s, and thereafter remained relatively constant with significant inter-annual variations. The increase in nitrogen loading from the 1960s onward can be attributed primarily, and almost exclusively, to increased use of nitrogen fertilizer by row-crop agriculture (Goolsby et al., 1999). Total phosphorus loads did not change significantly during this period. An increase in phosphorus occurred somewhat earlier—shortly after World War II—with the advent of phosphorus-based detergents.

Figure 6-3 presents modeled estimates of the relative contributions of nitrogen and phosphorus to the northern Gulf of Mexico from various sources. The figure shows that greater than 70 percent of loadings from both nitrogen and phosphorus emanate from agricultural sources (Alexander et al., 2008).

The growth and persistence of the hypoxic zone, the nutrient loadings that contribute to it, and management plans in response to it, are reflected in several recent reports and initiatives (Box 6-1). These reports reach the general conclusions that:

BOX 6-1
Recent Studies and Initiatives

Ongoing work of U.S. Geological Survey SPARROW water quality modeling. A team of USGS scientists has been employing a spatially-referenced regression on watershed attributes (SPARROW) water quality model to determine spatial patterns in nutrient yields across the Mississippi River basin (Alexander et al., 2008). Among other findings the SPARROW studies show that a small number of watersheds—several from the Corn Belt region and several from along the lower Mississippi River—contribute a large percentage of the basin's total nutrient yields.

Ongoing work supported by the National Oceanic and Atmospheric Administration's Center for Sponsored Coastal Ocean Research. This program has supported most of the academic and federal research on the dynamics, causes, and impacts of northern Gulf of Mexico hypoxia since 1990, and continues to support this work. Results from these studies supported most of the oceanographic and ecological findings in the integrated assessments conducted in 2000 and 2007 for the Gulf of Mexico Task Force.

Report from the EPA Science Advisory Board report on Gulf Hypoxia. This extensive 2007 report summarizes and evaluates a large body of previous scientific studies of the hypoxic zone. The report confirms the scientific consensus that contemporary changes in the hypoxic zone are driven primarily by nutrient fluxes from the Atchafalaya and Mississippi Rivers (USEPA, 2007). It also concluded that at least a 45 percent reduction in both nitrogen and phosphorus fluxes would be required to reduce the size of the hypoxic zone (ibid.).

Gulf of Mexico Task Force and Hypoxia Action Plan. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Task Force) issued a 2001 "action plan" in response to a directive in the 1998 Harmful Algal Bloom and Hypoxia Research Control Act (P.L. 105-383; reauthorized in December 2004 as P.L. 108-456). The Task Force issued a subsequent action plan in 2008. Both reports listed a goal for reducing the size of the Gulf hypoxic zone to a 5-year running average of less than 5,000 square kilometers (USEPA, 2001; 2008).

NRC Studies of Mississippi River Water Quality and the Clean Water Act. Two separate NRC committees issued reports in 2007 and 2008 on Mississippi River water quality issues and challenges. The 2007 NRC report focused on issues of water quality standards, monitoring, and interstate water quality coordination. The 2008 report addressed the topics of initiating pollutant control programs, alternatives for allocating nutrient load reductions, and documenting the effectiveness of pollutant loading reduction strategies.

The Mississippi River Basin Healthy Watersheds Initiative sponsored by the U.S. Department of Agriculture The USDA's Natural Resources Conservation Service (NRCS) expects to provide $320 million over a four-year period to farmers in select watersheds across the river basin to voluntarily implement conservation practices that control nutrient runoff; improve wildlife habitat; and maintain agricultural productivity.

1) changes in the hypoxic area in the northern Gulf of Mexico are primarily related to nutrient fluxes from the Mississippi-Atchafalaya River Basin;
2) changes in the extent and duration of hypoxia today appear to be more sensitive to inputs of nutrients than in the past;
3) there are early signs of deleterious long-term effects on living resources; and

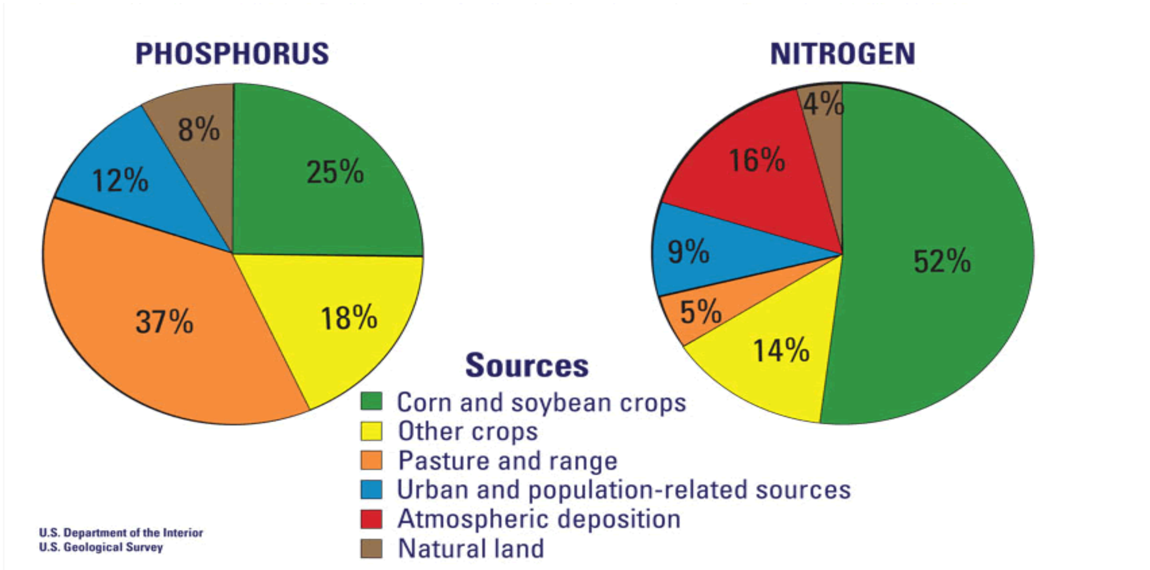

FIGURE 6-3 Sources of Nutrients Delivered to the Gulf of Mexico.[1]
SOURCE: Data from Alexander et al., 2008.

4) reducing the size of the hypoxic zone and improving water quality in the Mississippi-Atchafalaya River basin will require considerable reductions in nitrogen and phosphorus loads. One estimate is that each source will need to be reduced by at least 45 percent from the 1980-1996 average (USEPA, 2007).

Missouri River Sediment Management Actions and Implications for Nutrient Loadings

This section discusses two approaches to considering whether the current sediment management practices associated with the Corps of Engineers' Missouri River shallow water habitat projects, as well as possible future actions, might significantly contribute to Gulf hypoxia. First, potential nutrient load increases from these SWH projects are compared to current Missouri River nutrient load, and to the overall load delivered by the Mississippi River to the Gulf to determine the relative significance of potential load increases.

Describing this relative change in nutrient loadings from these Missouri River projects, in itself, does not address whether there may be an effect on the hypoxic zone. Therefore, a second step draws upon on published scientific literature relating changes in nutrient loads to the areal extent of hypoxia, and evaluates the ultimate potential impact in the northern Gulf.

[1] Some other estimates of these relative contributions (e.g., USEPA, 2007) produce somewhat different values.

Corps of Engineers Shallow Water Habitat Projects

The Corps of Engineers Shallow Water Habitat projects will result in releases of both nitrogen and phosphorus to the river because much of the topsoil portion of the sediment disposed of in the river has been heavily fertilized during its cultivation. Phosphorus loadings to the river from these projects, however, are likely to constitute a much greater fraction of the current load than additional nitrogen loadings. For example, the potential nitrogen load from the Jameson Island (Missouri) restoration project (described in Chapter 5) has been estimated as 0.23 percent of the 1994-2006 average loads at Hermann, Missouri (Jacobson et al., 2009). This is compared to the order-of-magnitude-higher estimate for phosphorus—2.6 percent of the load at Hermann—for the same project. In addition, the Missouri River provides 13 percent of the total nitrogen (TN) loads (9.8 percent of the nitrate load) to the Gulf, compared to 20 percent of the total phosphorus (TP) loads (Aulenbach et al., 2007 as summarized in EPA, 2007, Table 3). Therefore, because it is unlikely that total nitrogen loads from the SWH projects will be significant compared to current nitrogen loads transported in the Missouri River, the remainder of this discussion will focus on total phosphorus.

Currently, the total phosphorus load to the Gulf is estimated to be 154,300 metric tons per year, with the contribution of the Missouri River to this total load estimated to be between 16.8 and 20 percent (Aulenbach et al., 2007 as summarized in USEPA, 2007, Table 3; and Alexander et al., 2008). To compare the potential contribution of phosphorus from the Corps SWH projects, the same estimates of the total sediment volume these projects deliver to the river—34 million metric tons (Mt)/year—are used here as were discussed in Chapter 5 (Jacobson et al., 2009).

The rate at which these sediments, and the associated phosphorus within those sediments, are transported is important in determining their downstream effects. Under most conditions, sediment settling and storage processes in the Missouri and Mississippi River channels will attenuate the load and spread delivery to the Gulf over a long period of time (e.g., years). However, to arrive at an upper bound estimate of downstream impacts, one could make an assumption that all of this sediment is transported to the Gulf in a single year.

If one makes this upper-bound assumption of all this sediment being transported to the Gulf each year, and if sediment contains an average 443 mg-TP/kg of sediment with a standard deviation of 129 mg (Jacobson et al., 2009; summary of Jameson Island restoration-related sampling identified in: CDM Federal Programs Corporation, 2007, Table 4-1), the increased total phosphorus load to the Gulf would range between roughly 10,700 and 19,400 metric tons /year.

This represents 6-12 percent of the current phosphorus load from the Mississippi basin.

Again, and for purposes of illustration, this figure represents an upper bound estimate of additional phosphorus transported downstream from all SWH construction-related sediment released into the Missouri River. Actual values are almost assuredly to be less than this estimated, upper end range.

Potential Sediment Bypass Around Gavins Point Dam

It also is possible to estimate the potential total phosphorus load to the Gulf resulting from moving sediment around Gavins Point Dam—an aggressive, perhaps unlikely—sediment management measure (and described in Chapter 5). An estimated 6 million tons/year of sediment enter Lewis and Clark Lake behind Gavins Point dam (see Chapter 5; Coker et al., 2009). Using the same range of phosphorus content as in the sediment from the Jameson Island project, assume that no more than 6 million tons per year will pass the dam, and further assume that that all this sediment moves to the Gulf each year, then between roughly 1,900 and 3,500 metric tons/year of phosphorus (P) would reach the Gulf each year. This represents 1-2 percent of the current load delivered by the Mississippi River to the Gulf (see Table 6-1). Similar to the assumptions for the construction-related sediment releases above, this estimate of added loading represents an upper bound and does not consider the role of the river channel in attenuating the load and spreading its delivery over multiple years. Actual deliveries are highly likely to be less than this upper bound estimate of 1-2 percent.

To summarize, an upper bound estimate of the increase in phosphorus loadings to the Gulf as a result of the Corps shallow water habitat (SWH) projects is a 6-12 percent increase (Table 6-1). Similarly, an upper bound estimate of the downstream deliveries of bypassing sediment around Gavins Point Dam is that phosphorus loadings would increase total phosphorus load by roughly 1-2 percent. Both these estimates represent upper bounds. In reality, sediment deposition processes in the Missouri and Mississippi River channels would reduce loads delivered to the Gulf, and actual downstream deliveries would be less than these values.

TABLE 6-1 Comparisons of Potential Annual Total Phosphorus (TP) Augmentations to the Missouri River and Gulf of Mexico (values in metric tons of TP/yr)

Summary Comparing Potential Annual Total Phosphorus (TP) Load Augmentation (Metric Tons-TP/Yr)	
CURRENT AVERAGE LOAD TO GULF FROM MISSISSIPPI RIVER BASIN:	154,000
CURRENT LOAD FROM MISSOURI RIVER: (17-20 percent of total load to Gulf)	25,536–30,400
ESTIMATED UPPER BOUND LOADS FROM CORPS SWH PROJECTS: (6-12 percent of total load to Gulf)	10,700–19,400
ESTIMATED UPPER BOUND LOADS FROM GAVINS POINT DAM BYPASS: (1-2 percent of total load to Gulf)	1,900—3,500

SOURCES: Data from Alexander et al., 2008; Aulenbach et al., 2007; Coker et al., 2009; Jacobson et al., 2009; USEPA, 2007. See accompanying discussion in text.

Potential Effects on Gulf Hypoxia

In addition to providing estimates of additional phosphorus loadings from two alternatives discussed above, a second question is whether these increases could have a measureable effect on hypoxia. Conducting the original research and modeling exercises necessary to address this second question was beyond this committee's resources and composition. However, there are two articles that summarize research that derived response curves that relate changes in areal extent of hypoxia to delivered phosphorus load (Greene et al., 2009; Scavia and Donnelly, 2007).

Given the considerable year-to-year variability in measured hypoxic area, a significant and sustained change in delivered total phosphorus load would be required to cause a clear and significant change in the size of the hypoxic area. Given this significant inter-annual variability in measured hypoxia, the confidence envelope on the model is used as a measure of a significant change in hypoxia. These error bounds in Figure 6-4 represent a confidence interval of approximately plus or minus 20 percent. This figure thus is used to represent a clear and a significant response to changes in total phosphorus load.

One of these papers (Scavia and Donnelly, 2007) presents results from a biophysical model that relates the areal extent of Gulf hypoxia to April-June total phosphorus loads. The modeled response curve from this study (Figure 6-4) suggests that reducing the areal extent of hypoxia by 20 percent from the 2001-2007 average of 16,500 km^2, would require a reduction in the spring total phosphorus load of approximately 200 metric tons/day (ibid.). The curve also suggests that significantly more than 200 metric tons/day of phosphorus would be required if the hypoxic area is to permanently increase by 20 percent. This is because, as shown in Figure 6-4, the hypoxic area increases with increasing P loads, but at a decreasing rate.

A 2009 study developed a regression model relating hypoxic area to February total phosphorus concentration in the Mississippi River (Greene et al., 2009). That regression equation suggests that a 20 percent increase in hypoxic area requires a 20 percent increase in river concentration of total phosphorus (TP) above the current average of 210 μg-TP/l (Greene et al., 2009, Figure 3b)—or an increase of 42 μg-TP/l. River total phosphorus concentration is fairly constant between February and June so the increase of 42 μg—TP/L can be assumed to occur each of these months.

Average April-June river discharge is 33,000 m^3/sec (Greene et al., 2009). Multiplying the required change in river concentration (42 μg—TP/l) by the discharge rate (33,000 m^3/sec) results in a required TP load increase of 122 metric tons/day. Thus, based on the models presented in the two papers, an increase of 100-200 metric tons/day in the spring load is needed to produce a measureable change (e.g., 20 percent) in the Gulf hypoxic area.

These models were calibrated with spring phosphorus loads. Load estimates from the Corps of Engineers Missouri River shallow water habitat projects are annual amounts, so for comparison, spring load values have to be converted to annual load values. Approximately 34 percent of the annual phosphorus load is delivered in April-June (USEPA 2007, Figure 22, summarizing data from Battaglin, 2006; and Aulenbach et al., 2007). Assuming 100-200 metric tons/day applies for the 91 days in spring (April-June) results in a range of 26,765 to 53,530 metric tons/year. The midpoint value in this range is 40,150 metric tons/year. Again, this value

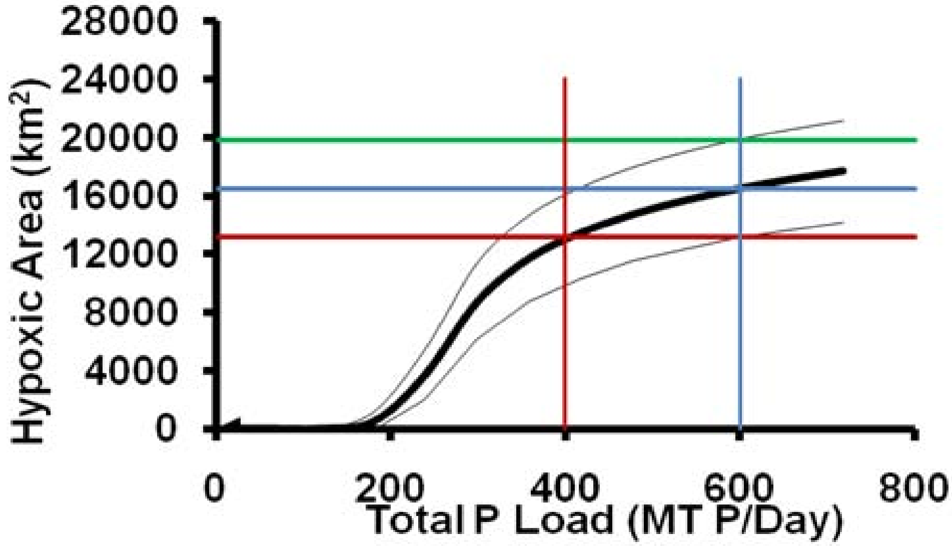

FIGURE 6-4 Modeled relationship between Total Phosphorus loads to the Gulf of Mexico and changes in areal extent of hypoxic zone. Solid black line represents the response curve, grey lines represent error bands around the curve. The blue lines represent the 2001-2007 average areal extent of the hypoxic area (16,500 km^2) and its corresponding spring load. The red lines represent a 20 percent decrease in hypoxic area and its corresponding 200 metric tons/day spring load reduction. The green line represents a 20 percent increase in hypoxic area.
SOURCE: Redrawn, with permission, from Scavia and Donnelly, 2007. © 2007 by American Chemical Society.

represents an estimate of additional total phosphorus that would be required for a substantial (20 percent) increase in the areal extent of Gulf hypoxia.

For purposes of comparison, 40,150 metric tons/year figure is 2.1-3.7 times larger than the upper bound estimated range of 10,658—19,418 metric tons per year of phosphorus estimated from the Corps SWH projects, and 11-21 times the estimated range from moving sediment past Gavins Point Dam. Thus, even the upper bound estimates of additional total phosphorus from the shallow water habitat projects and the bypass of sediments around Gavins Point Dam are considerably less than the amounts of additional total phosphorus necessary to result in a distinct increase in the areal extent of the Gulf hypoxic zone.

Measurements of the Hypoxic Zone

In addition to annual variation in nutrient concentrations in rivers that discharge into the northern Gulf of Mexico, year-to-year variation in hypoxic areal extent is controlled by several factors in addition to nutrient concentration in rivers that discharge to the Gulf. One factor is the volume of water discharge from the Mississippi and Atchafalaya rivers; lower flows will result in lower nutrient delivery and a smaller hypoxic zone. The areal extent of the hypoxic zone is measured annually, in late July, by a team of scientists from the Louisiana Universities Marine Consortium (see www.lumcon.edu). The timing of this single cruise does not always coincide with the maximum extent of the hypoxic zone in the survey year because the area of hypoxic waters can be affected by several factors that vary from year to year. For example, strong winds will mix the water column and temporarily aerate bottom waters. Therefore, if wind mixing is particularly acute just prior to the monitoring cruise, the measured hypoxic zone can be considerably smaller than just prior to the major wind event, or a few weeks after the event. Weather conditions and responsive oceanographic processes can also alter the physical structure of the hypoxic region. For example, the areal extent of the hypoxic zone measured in 2009 was one of the smallest recorded. However, as explained by the science team conducting the measurements, this areal extent was mainly a function of local weather and wind conditions:

> …persistent winds from the west and southwest in the few weeks preceding the mapping cruise likely pushed the low oxygen water mass to the east and 'piled' it up along the southeastern Louisiana shelf. The area of hypoxia (less than 2 mg/liter), and often anoxia (no oxygen) on the eastern part of the study area was an unusually thick layer above the bottom and was severely low in oxygen, usually less than 0.5 mg/L. A similar situation was documented in 1998 following persistent winds from the west, that is, a smaller footprint but a larger volume of low oxygen (LUMCON, 2009).

Given the multiple causes of the year-to-year variation in the area of hypoxia in the northern Gulf of Mexico, it is not appropriate to relate discharges from select sites of relatively small nutrient loadings across the river basin with changes in the areal extent of the hypoxic zone in any given year. At the same time, the consensus on the role of nutrient loading from across the river basin as a contributing factor remains, and sustained and substantial reductions in nutrient loads from the major sub-basins are still being recommended (e.g., USEPA, 2008)

Available estimates of total phosphorus loads from the Corps of Engineers Missouri River restoration projects are small compared to current loads from the Missouri River and the Mississippi basin. They thus appear unlikely to influence the areal extent of the hypoxic zone. That being said, the Corps of Engineers Missouri River restoration projects, and any additional future projects, deliver additional nutrients to the river and Gulf at a time that federal and state agencies, and a variety of nongovernmental organizations, are seeking ways to reduce nutrient loadings across the Mississippi River basin.

WATER QUALITY CRITERIA FOR SEDIMENT AND NUTRIENTS

This report does not intend to suggest that load increases of any size or in any location can be ignored in permitting for the discharges of sediment and nutrients into waterbodies. Increases in nutrient loads from any source, including that associated with sediment discharges from mitigation and restoration projects, may have to be avoided or mitigated if avoidance would be counter to meeting sediment enrichment objectives for the Missouri River. In fact, under current EPA guidelines for setting nutrient criteria, "downstream" effects may need to be recognized in setting nutrient criteria for discharges to the Missouri River mainstem. This section discusses the setting of water quality criteria for nutrients.

Clean Water Act (CWA) Section 303(c) requires states to develop water quality standards that include designated uses of water bodies, water quality criteria that are necessary to protect those uses, expressed in either numeric or narrative form, and prevent water bodies from being degraded with reference to their current condition (anti-degradation). States submit their water quality standards to EPA for review and approval. The Missouri Clean Water Commission actions to limit discharges for sediment to the river from Corps' ESH and SWH restoration activities found that those activities were in violation of Missouri's water quality standards (see Chapter 3).

In recent years and for the specific case of nutrients, the EPA has offered states guidance for the development of numeric nutrient criteria (USEPA, 2009a). As of 2008, only one of the ten states in the Missouri River basin (Montana) had adopted numeric criteria for nutrients. The remaining states, including Missouri, had narrative criteria. For example, Kansas says this about total suspended solids: "Suspended solids added to surface waters by artificial sources shall not interfere with the behavior, reproduction, physical habitat or other factors related to the survival and propagation of aquatic or semiaquatic life or terrestrial wildlife" (Section 28-16-28e [Surface Water Quality Criteria] of the Kansas Administrative Regulations).

A recent EPA Inspector General report recommended the need to accelerate the numeric criteria development process and focused especially on states in the Mississippi-Missouri River basins that are the main contributors to hypoxia in the Gulf of Mexico (USEPA, 2009b). Within the basin, the EPA Region 7 supported an effort to develop guidance that would assist the basin states in adopting numeric nutrient criteria for the shared mainstem Missouri River. As this effort to develop numeric criteria was underway, with limited resources, EPA actions in Florida gained national attention. The EPA required replacing Florida's narrative sediment and nutrient criteria with numeric criteria and expected such numeric criteria to be protective of designated uses of the water body itself as well as downstream waters. Clearly, the EPA effort to define numeric water quality criteria for the Missouri River is part of an ongoing national agency effort to replace narrative with numeric criteria that protects local and downstream waters.

Nutrient Criteria for the Missouri River

The analytical approach to developing numeric criteria has followed well-established national EPA protocols (see Baker et al., 2008). Although formal nutrient criteria for the Missouri River have not been proposed, the approach being used can be summarized as follows:

- A database of nutrient chemistry on the mainstem of the Missouri River, including the reservoirs, and the channelized and unchannelized sections was developed. Within these data the lower 25th percentile of TN and TP concentrations from the general distribution of nutrient concentrations in the water column was identified. This lower 25 percent was one method of selecting a numeric criterion for TN and TP. However, the water column data span a period from 1967-present and there are no known nutrient data representing pre-dam conditions (i.e., prior to 1955 when Gavins Point Dam was closed).

- A statistical analysis was done to relate metrics characterizing benthic macro-invertebrates and fish communities (such as number of species) and chlorophyll a concentrations to nutrients present in the water column. Then, water column concentrations of nitrogen and phosphorus that were associated with the ecologically best condition for the metric were identified as possible numeric criteria. However, it is unclear from the available reports what fish species were used for the fish community index and whether those species were native fishes.
- Literature and modeling sources were used to identify conditions that represent natural background or conditions without excessive algae, represented by chlorophyll a measurements. These are based on the general literature for streams (Dodds et al., 1998, 2002), and on a nationwide estimate of background concentrations of nutrients (Smith et al., 2003). However, the literature does not include information for the mainstem Missouri River.

The three evaluations above offer different approaches to setting nutrient criteria for water quality. Using these multiple lines of evidence, the next step is to define numeric total nitrogen (TN) and total phosphorus (TP) criteria for each major section of the Missouri River (e.g., unchannelized portions of the upper Missouri, main-stem reservoirs, reaches between reservoirs, unchannelized portions below reservoirs, and channelized portions of the river). The report to EPA offered draft numeric criteria for total nitrogen between 0.43 and 1.1 mg/l and total phosphorus between 0.05 and 0.1 mg/l for the different river segments (Missouri River Workgroup, 2008).

The application of this approach is consistent with nutrient criteria guidance for streams in general (USEPA, 2000) and is focused on protecting an aquatic life designated use. However, the process as applied **does not** take into account the historic sediment and phosphorus conditions on the mainstem of the Missouri river, and **does not** use the aquatic life that was native to the river as the designated use. This is despite the current and future restoration activities in the Missouri River—many of which seek to increase sediment supply in the river, to better represent pre-dam conditions, and to promote better habitat conditions for native endangered species such as the pallid sturgeon. Given the significance of particulate phases of phosphorus in natural waters—and the strong correlation between phosphorus concentrations and suspended sediment concentrations—neither can be considered in isolation.

There also has been an independent national EPA effort to develop approaches for the setting of numeric sediment criteria (USEPA, 2006), although numeric sediment criteria were not the intent of the Region 7 EPA (headquartered in Kansas City) supported nutrient criteria effort described above. The specific term for sediments as a pollutant that can cause impairment is suspended or bedded sediments (SABS) and encompasses suspended sediment, total suspended solids, bedload and turbidity. The EPA framework document is neutral about the direction of sediment impairment; that is, the sediment numbers in a water body can be too low or too high for the designated use. Also, the framework document acknowledges the role of dams in severely reducing sediment supply in many rivers. It states, for example:

> Sediment starvation caused by structures such as dams and levees is a problem in some ecosystems, ranging from the loss of native fish species and native riparian ecosystem structure in many dammed western rivers (e.g., Colorado River, Platte River, Missouri River) to the subsidence and loss of wetlands (e.g., Mississippi Delta in Louisiana).

However, the analytical approaches presented in the framework document for future development of numeric SABS criteria are almost entirely focused on situations where excess SABS are a cause of impairment, typically by smothering of benthic habitat or substrate needed for fish spawning. In the case of large rivers that have been dammed, and where there is good evidence of pre- and post-dam sediment loads, the SABS framework does not provide an analytical framework to help define criteria that recognize some level of sediments as necessary for the attainment of the designated uses, such as along the mainstem of the Missouri River where sediment-starvation conditions have led to bed degradation and loss of habitat for endangered species.

Water Quality and the Historic Missouri: A Reference Condition

As discussed in previous chapters the Missouri River has always carried a substantial sediment load. And that load, as well as the nutrients (especially phosphorus) that accompanied that load, created the conditions that supported the native flora and fauna that characterized the Missouri and that now are the focus of habitat and species protection and restoration efforts.

Sediments as Water Quality Impairments

Findings of water quality impairment due to sedimentation are commonplace in the U.S. and are the sixth most common cause of impairment in waterbodies (after pathogens, metals other than mercury, mercury, nutrients, and organic enrichment; USEPA, 2010a). In the Missouri River basin, there are several hundred water segments identified as impaired by sediments, most commonly in Montana, South Dakota, and Kansas (Figure 6-5). These waters are typically smaller creeks that drain watersheds on the order of hundreds of square miles are deemed to be impaired based, in most instances, on narrative criteria. Frequent causes of impairment are associated with croplands, livestock feeding operations, grazing in riparian lands, wastewater treatment plants, and stream bank modification.

The Missouri River basin is the site of waterbodies that are listed as impaired by excess sediment, and of restoration activities along the mainstem that seek to add sediment loads to the river. These very different settings are not necessarily in conflict and they point to the importance of recognizing that not all sediments and all rivers are the same. As was discussed in

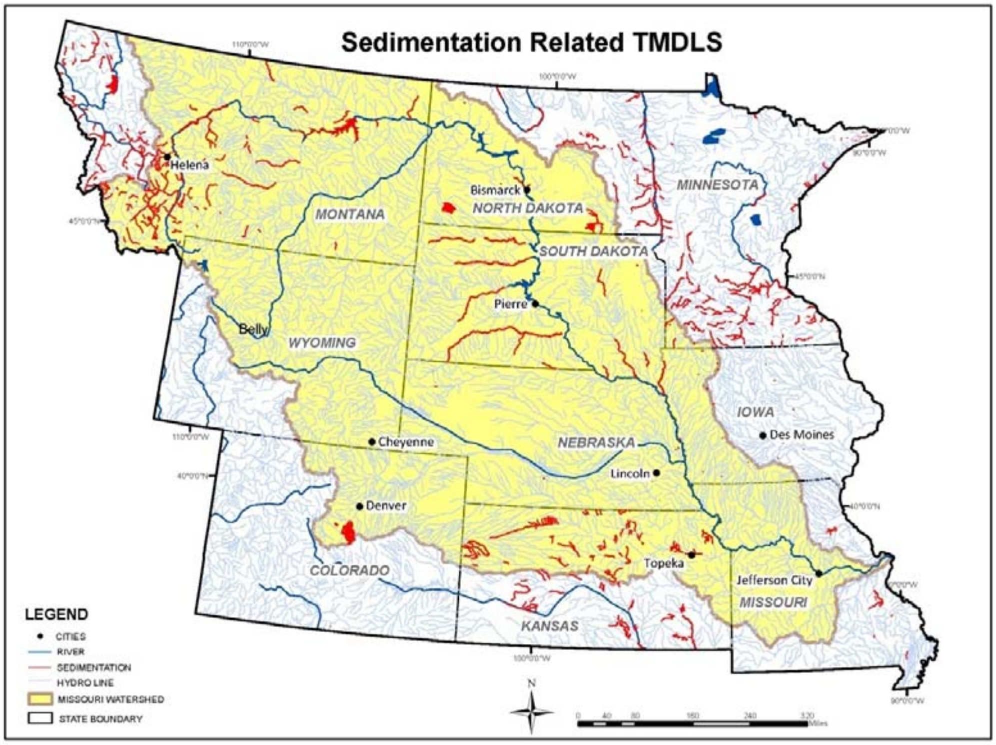

Figure 6-5. Missouri River basin streams that are impaired by excess sediments and for which TMDLs have been developed.
SOURCE: USEPA, 2010b.

Chapter 2, excess sediment loadings to historically clear headwater streams can be a cause of impairment, whereas release of large grain-size sediments to the mainstem—often being material that has been trapped by the river control structures of the Bank Stabilization and Navigation Project over the years—may be essential to attaining designated uses that support native species.

Nutrients Associated with Sediments as Water Quality Impairments

As previously discussed, phosphorus is a nutrient closely correlated with sediment. As a result, it is likely that there were background concentrations of phosphorus in the Missouri River prior to the construction of the mainstem dams and river control structures that were part of the ecosystem that supported populations of the native species. However, those levels of total phosphorus need to be estimated because direct measurements were not conducted prior to the 1960s. No such pre-dam estimates of total phosphorus in the Missouri River have been reported, and are estimated below for the purpose of this discussion.

One approach to estimate historic phosphorus concentrations in the Missouri basin is to use the suspended sediment concentrations, which have been reported for well over a hundred years, and estimates of particulate phosphorus concentrations from other less-developed basins. Prior to the construction of the major dams, median sediment concentrations in the Lower Missouri River were approximately 2,000 mg/l (medians range from 1,920 mg/l to 2,330 mg/l at different stations; Blevins, 2006). More recently, the median concentrations are approximately 400 mg/l (456 and 378 mg/l at two stations; Blevins, 2006). Pre-development particulate phosphorus concentrations (mass of phosphorus per unit mass of sediment) can be assumed to range from 200-650 mg/kg, at the low end for phosphorus-poor systems and at the high end for a basin like the Amazon (Berner and Rao, 1994). There are reports of even higher particulate phosphorus concentrations in less developed basins (Meybeck, 1982; Melack, 1996), but the 200-650 mg/kg suffices for the present discussion.

In comparison, phosphorus in sediments in the Mississippi River now average 1,085 mg/kg (Sutula et al., 2004). Using a range of 200-650 mg/kg of particulate phosphorus to represent a range of background conditions, pre-dam background water column concentrations of 0.4-1.3 mg/l is a reasonable estimate (assuming that the particulate forms dominate the total phosphorus).

Phosphorus concentrations in the channelized portions of the Missouri River today range between 0.2 and 0.6 mg/l, reflecting more phosphorus-enriched particulates, even though the total quantity of suspended sediments is lower (Baker et al., 2008). Although there is much uncertainty in assuming a range of phosphorus concentrations without the benefit of historic data to calculate historic background levels, the approach employed above suggests that modern-day total phosphorus concentrations in the lower Missouri River are not necessarily higher than the historic background.

As another approach, a nation-wide analysis of background nutrient concentrations estimated median background total phosphorus in the streams of the eco-regions in the Missouri River basin at approximately 0.06 mg/l (Smith et al., 2003). This approach used regressions between land use and concentrations in small undeveloped basins as the underlying method, and may not fully reflect the dramatic changes in sediment transport regime that have occurred in the Missouri River basin. This value is considered too low given the historic range of suspended sediments, and the likely range of particulate phosphorus in undeveloped watersheds presented above, but this difference does illustrate the uncertainty in understanding the background phosphorus load in the system.

The actions of the Missouri Clean Water Commission highlight the need for closer integration of the nutrient criteria development process and water quality management decision making. The federal agencies, working cooperatively with all the states, can reconcile the setting sediment and nutrient criteria with the Endangered Species Act and congressionally mandated programs to avoid jeopardy to three engendered species and restore the Missouri River Ecosystem. However, recent EPA supported water quality criteria development efforts for the mainstem Missouri were conducted with limited time and funding and not able to fully consider the needs of native species.

Development of numeric criteria for sediment and nutrients should be based on further understanding of the sediment and phosphorus history of the river, and the effects on native species, as that information becomes available through the MRRP and other ongoing studies. Because the data collection, analytical and collaboration processes needed to develop narrative possibly numeric criteria can require significant resources, an opportunity to realize efficiencies in that process and reduce the resource requirements can be realized by incorporating the criteria development process with the analyses underway under the MRRP, to include reliance on MRRIC to mediate disagreements among federal and state agencies on proposed water quality criteria.

Sediment Releases and Water Quality Compliance

The development of narrative or numeric criteria take such factors into account in setting limits on sediment and phosphorus discharges to the mainstem river and as a basis for regulating such discharges. However these criteria are set, regulatory consistency will require that all sources seek to avoid making discharges, or if such discharges cannot be avoided, offset increased loads with reductions in other places or from other actions. Also, if there is a need for such offsets when sediment discharges to the river are made for native species restoration, they can be established only if there is adequate monitoring of the sediment characteristics and the phosphorus in the sediments released. Furthermore, although phosphorus is a key sediment-associated constituent of concern, other chemicals of concern for water quality management include trace metals, such as lead and mercury, and trace organics such as PCBs and organo-chlorine pesticides and are present in Missouri River sediments in some locations (Echols et al., 2008). In general, however, knowledge of total phosphorus content or knowledge about other chemical constituents at restoration projects is limited. The release of sediments from restoration projects, both the total quantity and chemistry, needs to be better understood through monitoring as construction activities in support of restoration along the Missouri River. Knowledge of the characteristics of the sediment, as well as concentrations of the constituents in sediment released, can be used to judge the suitability of release of sediment into the Missouri River.

SUMMARY

The Corps of Engineers shallow water habitat projects along the Missouri River have prompted concerns about possible water quality impacts downstream and into the northern Gulf of Mexico. As this chapter has explained, these concerns are strongly related to the development of water quality standards and nutrient criteria, historical water quality conditions of the Missouri River, and the monitoring of sediment discharges into the Missouri.

An upper bound estimate of the increase in phosphorus loadings to the Gulf as a result of the Corps SWH projects is a 6-12 percent increase. Similarly, an upper bound

estimate of the downstream deliveries of bypassing sediment around Gavins Point Dam is that the additional sediment would increase total phosphorus load by roughly 1-2 percent. Both these estimates represent upper bounds. In reality, sediment deposition processes in the Missouri and Mississippi River channels would reduce loads delivered to the Gulf, and actual downstream deliveries would be less than these values.

A comparison of potential phosphorus loads from Corps SWH projects, with load increments required to produce measureable changes in the areal extent of Gulf hypoxia, shows that these projects will not significantly change the extent of the hypoxic area in the Gulf of Mexico. Additional comparisons of other alternatives for reintroducing sediment to the river—namely, bypassing sediment around Gavins Point Dam—yield a similar conclusion that they will not significantly change the areal extent of the hypoxic zone.

There also have been questions raised about the relationship between loadings from the SWH projects in a given year, and possible associated changes in the areal extent of Gulf hypoxia in the same year.

In addition to nutrient loadings, multiple factors—including meteorologic, hydrodynamic, and timing factors—affect the size of the hypoxic zone each year. Given the relatively small volumes of sediment loadings from the Corps' Missouri River ESH and SWH projects, it is not appropriate to relate changes in the areal extent of the hypoxic zone to sediment and nutrient loadings from Missouri River ESH and SWH projects in any given year.

The sediment that was essential to pre-regulation river morphology and landforms and to the turbidity that supported the ecosystem of native species had certain characteristics. Development of narrative or numeric water quality criteria that is sensitive to these historic conditions will consider such factors in setting limits on sediment, as well as phosphorus, discharges to the mainstem river and as a basis for regulating such discharges. Native species recovery objectives can be reconciled with the requirements of the Clean Water Act by basing waterbody use designation and associated criteria on aquatic life use that recognizes the needs of native species.

The mainstem Missouri River historically carried a large sediment and nutrient load that was important to the evolution and survival of native flora and fauna. These pre-regulation characteristics should be considered in the process of developing water quality standards for the Missouri River.

The federal agencies that are partners in the MRRP, and other major Missouri River ecosystem program and initiatives, should collaborate with ongoing EPA nutrient criteria guidance development process to achieve agreement among themselves and with the states on designated uses for the river, by river segment, to reflect requirements for native species. As a result of this effort, EPA should support states that revise their existing narrative criteria for the mainstem Missouri River in order to reflect requirements for native species, even if such separate narrative sediment and nutrient criteria later are replaced by numeric criteria. As appropriate, downstream considerations (such as Gulf hypoxia) may be considered in the setting of phosphorus criteria.

There has been a good deal of discussion regarding Corps of Engineers habitat restoration actions along the Missouri River that introduce sediment to the main channel. Specifically, some parties have asserted that private entities are held to a higher standard of permitting and monitoring than a federal agency such as the Corps of Engineers. In order to obtain better, more systematic information on sediment dynamics along the river and specific activities that introduce sediment, it is important that all major activities—whether private sector or governmental—that discharge sediment be similarly monitored and evaluated.

All actions by the Corps of Engineers that discharge sediment to the Missouri River either during project construction or through erosion following construction, should be subjected to monitoring requirements for sediment physical and chemical characteristics. This monitoring should be conducted to ensure that sediment or other pollutants discharged to the river comply with applicable water quality criteria.

7
Science, Policy, and Future Decision Making along the Missouri River

As one of the nation's largest river systems, the Missouri River is of great importance to numerous states, cities and communities, and citizens. This report has documented the fundamental transformation of Missouri River sediment processes during the nineteenth and twentieth centuries. The pre-regulation river was a free-flowing system characterized by variable channel conditions and a flooding regime that transported vast amounts of sediment and provided rich and varied habitat for its native species. The engineering works built under the Pick-Sloan Plan and the Bank Stabilization and Navigation Project harnessed the river to meet social demands and preferences of the era. Among the consequences and impacts of those engineering works were sharp changes in the river's sediment processes and major alterations of habitat for native bird, fish, and plant species.

Since passage of the Pick-Sloan Plan and the BSNP in the mid-1940s, the U.S. Congress has assigned lead responsibility for Missouri River flow management to the U.S. Army Corps of Engineers. As new laws, such as the Endangered Species Act, were passed, original management authorities have been redefined. Recent congressional directives have created opportunities for river users to have a more direct voice in Corps river management decision making, and have focused greater attention on ecosystem recovery. These new initiatives include the Missouri River Recovery and Implementation Committee (MRRIC), the Missouri River Ecosystem Restoration Plan (MRERP), and the Missouri River Authorized Purposes Study (MRAPS), all of which will figure prominently in future Missouri River management decisions. Not surprisingly, the creation of these new programs, layered on top of existing programs for ecosystem mitigation, Master Manual revisions, and Biological Opinion compliance, has led to confusion regarding relationships and boundaries among these new initiatives and the older, existing governance system. Although the new initiatives may ultimately improve Missouri River decision making, they have added to institutional complexity.

The Missouri River basin has seen its share of disputes over shared water and sediment resources. Not only have there been differences of opinion regarding the Corps of Engineers mitigation projects along the lower river, basin states often have held different views on appropriate reservoir release schedules and other decisions. One impetus for the spate of new initiatives is to address continuing environmental and socio-economic changes along the river, and to mediate and reconcile the often sharp differences of opinion over operations and other decisions affecting flows of water and the transport and deposition of sediment.

As a consequence of studying the role of sediment in Missouri River management decisions, this committee made several observations regarding river resources and the role of science that fall into two broad categories—1) trade-off choices and resource limits, and 2) science and decision making. The following two sections are presented in the spirit of contributing to river management decision making and expectations regarding the role of the science community in such decisions.

Trade-off Choices and Resource Limits

In many ways the Missouri River is no different than other large U.S. river systems, as difficult choices are inevitable and priorities among competing uses ultimately must be established—especially during periods of high and low river flows. Furthermore, preferences for the goods and services provided by the Missouri dam and reservoir system have changed and shifted over time. Some differences of opinion regarding water releases and mitigation activities along the Missouri River have been highly controversial. This may not always be the case, however, and future conditions on the Missouri River may provide better opportunities for compromise and common understanding.

The Missouri River was fundamentally altered and changed during the twentieth century. These changes represented a conscious, national policy decision to transform the free-flowing, pre-regulation Missouri River into a system with dams, reservoirs, and a commercial navigation channel. The installation and operation of this extensive water control infrastructure produced many social benefits. This also resulted in unforeseen costs, such as the loss of habitat for native species that may have been under-appreciated, while most of the dams and river training works were being built. For example, nearly 3 million acres of riverine and floodplain habitat were altered, and dozens of native fish species today are "now listed as rare, uncommon, and/or decreasing across all or part of their ranges" (NRC, 2002).

Conflict along the river today generally revolves around trade-offs. For example, some parties today desire to regain some functions and benefits of the pre-regulation Missouri River. In most cases, however, an action to regain pre-regulation benefits will result in an existing user or sector losing some current, post-regulation benefits. When the Corps of Engineers adds sediment to the Missouri River as part of its mandate to improve habitat for native species, agricultural producers and other parties elsewhere in the Missouri basin may feel that they bear "unfair" obligations to limit erosion. Efforts to create habitat can be perceived by those who use the channel for navigation as threatening the channel's useful depth and width. Other examples of these trade offs abound: a higher spring rise of the Missouri River to benefit native species poses the potential for increased flooding for communities along the river; drawdowns of Missouri River reservoirs to augment flows for navigation impacts reservoir-based recreation and reduces water supplies in upstream states, and; removing revetments along the navigation channel in the name of ecosystem restoration may threaten farmland and infrastructure, as well as reduce depths of the navigation channel. Failure to acknowledge these realities and limits may contribute to lingering disputes and may confound effective decision making. There also may be instances in which small, incremental changes can provide ecosystem benefits without greatly affecting other uses. But these instances are difficult to identify, and they do not require major changes in river operations.

Future trade-offs among Missouri River users will be inevitable. The new programs created by Congress may help communicate information that highlights these trade-off choices and improves the chances of reaching consensus decisions and actions. Effective resolution of these trade-offs will require explicit acknowledgement of their existence, possible sources of conflict, as well as limits of the Missouri River's goods and services.

Science and Decision Making

This report offers recommendations and encouragement to create a sediment budget and data management system that is regional in scale and more easily accessible. It also highlights the scientific uncertainties that accompany many crucial river management decisions and offers advice to strengthen adaptive strategies to promote learning-while-doing. Non-scientific issues also are integral to the decision-making process. Examples of these issues include costs and benefits, social and cultural values, and a variety of federal and state laws. Conflicts regarding management decisions generally can be traced to scientific uncertainties, these other factors, or combinations thereof.

In some instances, the scientific community may be requested to provide advice to help resolve conflicts that are only partly rooted in science. For example, ongoing disputes along the Missouri River regarding discharges of sediment from Corps of Engineers projects into the river to comply with a federal mandate may go beyond basic science-related disagreements. Many current disagreements regarding Missouri River management appear to be related to policy interpretations or political questions related to social values.

Management of Missouri River sediment provides an example of the interplay among scientific and non-scientific factors. In making decisions on re-introducing sediment to the Missouri River or managing sediment to support mitigation activities, the Corps of Engineers and others should consider:

- Knowledge and uncertainties about life cycles and life histories of endangered species;
- Requirements for compliance with the Endangered Species Act and Clean Water Act;
- Availability of private lands for habitat mitigation projects;
- Social and cultural attitudes about the relative importance of species recovery and protection of property from erosion.

The scientific community has important roles in informing decisions regarding ecosystem restoration and species protection. Advice from the science community should address scientific questions about the form and function of the river. Scientific data, and analysis of those data, are crucial for developing management alternatives and predictions of responses of the ecosystem, and species of interest, to management actions. Scientists can help identify uncertainties and alternative outcomes that attend these actions, and can assist in estimating likely outcomes of various choices in the public decision process.

Scientific issues and questions can, however, blend into other related questions such as, "What happens if management of non-native, recreational fisheries is perceived by some as conflicting with recovery of endangered pallid sturgeon" and "How does acquisition of floodplain lands for mitigation or ecosystem recovery affect local economies?" Decision makers posed with these types of questions must consider not only possible effects on fishes and the broader biotic community, but also possible social and economic effects of a given action. All involved parties need to appreciate that there are distinctions between questions appropriate to scientific inquiry, and questions that are in the domain of policymaking. The role of science is to inform policy options, not abdicate policymakers from decision-making responsibilities.

Effective and appropriate use of science requires decision makers to acknowledge inherent scientific uncertainties, even as stakeholders may be frustrated if scientists are not willing or able to make clear and precise forecasts of river responses to a given management proposal. Use of "if -then" questions—*if* management action "x" is taken, *then* consequences "y" and "z" are likely to result—may help frame and focus scientific questions and direct scientists to explain areas of scientific consensus and the bases for that consensus. This "if-then" question format also means that when uncertainties lead to scientific disagreement, scientists still are responsible to identify uncertainties and describe their causes. There are instances in which decisions can and must be made in the face of scientific uncertainty. In these cases, scientists may frame predictions in terms of likely outcomes, probabilities, or a range of future scenarios, offering evaluations on the likelihood of different outcomes given the state of knowledge. Where uncertainties abound but decisions need to be made, adaptive management suggests basing decisions on a learning-by-doing approach.

Defining and adhering to boundaries between science and policy is a complicated and challenging process for decision makers, stakeholder groups, and scientists. Effective use of scientific information in Missouri River decision making will require these parties to acknowledge the different domains of science and policy, seek their respective boundaries, and appreciate the limits of knowledge about the river's natural systems.

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Appendix A
Guest Speakers at Committee Meetings

Federal Agencies

U.S. Army Corps of Engineers

- Chance Bitner, Kansas City
- Paul Boyd, Omaha
- Larry Cieslik, Omaha
- Craig Fleming, Yankton, South Dakota
- Mike George, Omaha
- Mary Miles, St. Louis
- Dan Pridal, Omaha
- John Remus, Omaha
- Jennifer Switzer, Kansas City, Missouri
- David Soballe, Vicksburg, Mississippi
- Ken Stark, Kansas City, Missouri
- Allen Tool, Kansas City, Missouri
- Cody Wheeler, Kansas City, Missouri

U.S. Environmental Protection Agency

- Jeff Robichaud, Kansas City

U.S. Fish and Wildlife Service

- Mike Olson, Bismarck, North Dakota
- Wayne Nelson-Stastny, Yankton, South Dakota
- Wayne Stancill, Yankton, South Dakota

U.S. Geological Survey

- Dale Blevins, Lee's Summit, Missouri
- Rick Wilson, Lincoln, Nebraska
- Joe Gorman, Council Bluffs, Iowa

State Agencies

Kristin Perry, Missouri Clean Water Commission, Jefferson City

Universities and Private Sector

Tim Cowman, Missouri River Institute, Vermillion, South Dakota
Denise Reed, University of New Orleans
Daniel Sheer, HydroLogics, Columbia, Maryland
A. Dan Tarlock, Chicago-Kent College of Law
Robert Twilley, Louisiana State University, Baton Rouge

Appendix B
Acronyms

ACT	(inter)Agency Coordination Team
BiOp	Biological Opinion
BSNP	Bank Stabilization and Navigation Project
CEM	Conceptual ecological model
CWA	Clean Water Act
CWC	Clean Water Commission (State of Missouri)
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ESA	Endangered Species Act
ESH	Emergent sandbar habitat
FWS	Fish and Wildlife Service
GAO	Governmental Accountability Office
HAMP	Habitat assessment program
ISP	Independent science panel
MRAPS	Missouri River Authorized Purposes Study
MRERP	Missouri River Ecosystem Restoration Plan
MRRIC	Missouri River Recovery Implementation Committee
MRRP	Missouri River Recovery Program
Mt	Million tons

ROD	Record of Decision
RPA	Reasonable and prudent alternative(s)
SWH	Shallow water habitat
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WRDA	Water Resources Development Act

Appendix C
Biographical Information

Committee on Missouri River Recovery and Associated Sediment Management Issues

Leonard A. Shabman, *chairman***,** is Resident Scholar at Resources for the Future. Previously he was professor of agriculture and applied economics in the Department of Agricultural Economics at the Virginia Polytechnic Institute and State University. Dr. Shabman's interests include economics, water resources, policy analysis, resource planning, wetlands, and pollution control. He also has served as an economic adviser to the Water Resources Council and scientific advisor to the Assistant Secretary of the Army, Civil Works. Dr. Shabman is a past member of the NRC Water Science and Technology Board (WSTB) and has chaired and been a member of several National Research Council committees. He received his Ph.D. degree in agricultural economics from Cornell University.

Thomas Dunne (NAS) is a professor in the Donald Bren School of Environmental Science and Management at the University of California at Santa Barbara. He is a hydrologist and a geomorphologist, with research interests that include alluvial processes; field and theoretical studies of drainage basin and hillslope evolution; sediment transport and floodplain sedimentation; and debris flows and sediment budgets of drainage basins. Dr. Dunne served as a member of the WSTB Committee on Water Resources Research and Committee on Opportunities in the Hydrologic Sciences and was elected to the National Academy of Sciences in 1988. He has acted as a scientific advisor to the United Nations, the governments of Brazil, Taiwan, Kenya, Spain, the Philippines, Washington, Oregon, and several U.S. federal agencies. Dr. Dunne is a recipient of the American Geophysical Union Horton Award. He holds a B.A. degree from Cambridge University and a Ph.D. degree in geography from Johns Hopkins University.

David L. Galat is Assistant Unit Leader at the U. S. Geological Survey's Missouri Cooperative Research Unit and Associate Professor in the Department of Fisheries and Wildlife Sciences, University of Missouri. Dr. Galat has been major advisor to over 20 graduate students and has taught university classes in fish and wetland ecology and the role of science in environmental decisions. His and his graduate student's research centers on ecology and restoration of aquatic resources of large rivers and floodplain wetlands, particularly within the Missouri-Mississippi basin. He is also interested in the role of science in informing natural resource policy and the application of adaptive management principles to ecosystem conservation and rehabilitation. Dr. Galat is an author of over 75 professional publications in aquatic and restoration ecology. Dr. Galat has served on numerous regional, national, and international committees dealing with river-floodplain ecology and restoration. Notable examples include the White House, Interagency Floodplain Management Review Team, National Research Council Committees on Water Resources Planning, and the National River Restoration Science Synthesis. He currently serves on the science advisory boards of the Upper Mississippi Navigation and Ecosystem Sustainability Program and the Platter River Recovery Implementation Program and is a member of the Collaborative Adaptive Management Network's (CAMNet) Core Advisory Group. He also serves on the editorial board of *River Research & Applications*. Dr. Galat received his B.S. degree from Cornell University and his M.S. and Ph.D. degrees from Colorado State University.

William L. Graf is University Foundation Distinguished Professor, Professor of Geography, and Interim Associate Dean for Research of the College of Arts and Sciences at the University of South Carolina. His research addresses two broad topics: geomorphology and hydrology of rivers, and the intersection of science and policy for public land and water. He has conducted research and served in science oversight positions associated with water quality, water quantity, aquatic and riparian habitats, and endangered species in a variety of ecosystems including the Klamath River of California and Oregon, streams of the Colorado Plateau, Colorado River, Rio Grande, Platte River, and the Everglades, as well as rivers in the Southeastern United States. He is also a National Associate of the National Academy of Sciences, and he has chaired or been a member of more than a dozen National Research Council committees and boards. He is a Past President of the Association of American Geographers; he was appointed to the Presidential Commission on American Heritage Rivers; and he is a member of the Environmental Advisory Board to the Chief of the U.S. Army Corps of Engineers. His several books and more than 140 papers and book chapters have resulted from funding by agencies such as the National Science Foundation, National Park Service, U.S. Army Corps of Engineers, U.S. Department of Energy, U.S. Geological Survey, U.S. Department of Justice, and a variety of state and local agencies. His work has been recognized by awards from the Association of American Geographers, Geological Society of America, and he has been awarded Guggenheim and Fulbright fellowships. President Clinton appointed him to the Presidential Commission on American Heritage Rivers, and he current serves on the Environmental Advisory Board to the Chief of the U.S. Army Corps of Engineers. His B.A. degree, M.S. Certificate in Water Resources Management, and Ph.D. degree are from the University of Wisconsin, Madison.

Rollin H. Hotchkiss is professor in the Department of Civil and Environmental Engineering at Brigham Young University. His current research includes developing a coupled upland-erosion, instream hydrodynamic-sediment transport model for assessing primary impacts of forest management practices on sediment yield and delivery; understanding the influence of successional development on periphyton scour; and the design of bridges and culverts for fish passage. Dr. Hotchkiss is chair of the Environmental and Water Resources Institute Watershed Council and associate editor of the *Journal of Hydraulic Engineering*. He is a member several organizations including the American Society of Civil Engineers, International Association of Hydraulic Research, and American Fisheries Society. Dr. Hotchkiss received his B.S. degree in civil engineering from Brigham Young University, his M.S. degree from Utah State University in civil and environmental engineering, and his Ph.D. degree in civil and mineral engineering from the University of Minnesota.

W. Carter Johnson is distinguished professor of ecology in the Department of Horticulture, Forestry, Landscape and Parks at South Dakota State University. Dr. Johnson's primary research interests are in streamflow regulation and riparian ecosystems, restoration of ecological and economic sustainability of western rangelands, multifunctional agriculture and agroecological restoration, and global climate change and prairie wetlands. Dr. Johnson has conducted most of his research in the Missouri River Basin. He received the W. S. Cooper Award in 1996 from the Ecological Society of America and has served on 3 previous NRC panels on large river systems. Dr. Johnson received his B.S. degree from Augustana College (Sioux Falls, SD) and his Ph.D. degree from North Dakota State University.

Patricia F. McDowell is professor of geography and professor of environmental studies at the University of Oregon. She teaches courses in fluvial geomorphology, watershed science and policy, and soils geography. Her current research focuses on geomorphic response of river channels and floodplains to human impacts and environmental change, and on river restoration. At the University of Oregon, she served as Associate Vice President for Research from 1990 to 1993 and as Chair of the Department of Geography from 1993 to 1996 and 2004 to 2008. She has served the NRC as a member on the *Committee on Research Priorities in Geography at the USGS* and the *Committee on Review of Methods for Establishing Instream Flows for Texas Rivers*. Dr. McDowell earned her B.Arch. and M.C.R.P. degrees from the Illinois Institute of Technology and her Ph.D. degree in geography from the University of Wisconsin.

Robert H. Meade is research hydrologist emeritus at the U.S. Geological Survey in Denver. His studies of rivers have centered on transport and storage of sediment in the Orinoco and Amazon Rivers of South America, long-term channel changes in Powder River of Montana, transport and deposition of riverine sediment in estuaries and coastal regions, and assessments of pollutants and sediments in the Mississippi River system. He served as a member of the NRC *Committee on the Review of the Louisiana Coastal Protection and Restoration Program.* Dr. Meade received his B.S. degree in geology in 1952 from the University of Oklahoma, and his M.S. degree (1957) and his Ph.D. degree (1960) in geology from Stanford University.

Roger K. Patterson is assistant general manager for Metropolitan Water District of Southern California, overseeing Metropolitan's strategic water initiatives for the Colorado River and Sacramento-San Joaquin Bay Delta. Mr. Patterson was the director of the Nebraska Department of Natural Resources from 1999–2005. He was responsible for water administration, water planning, flood-plain delineation, dam safety and the state databank. He represented Nebraska on interstate compacts, decrees and basin associations and led the state team in the settlement of U.S. Supreme Court cases on the North Platte and Republican rivers. Prior to his work in Nebraska, Patterson served 25 years with the U.S. Bureau of Reclamation. During his Reclamation tenure, he served as regional director in both the mid-Pacific region based in Sacramento and the Great Plains region headquartered in Billings, Montana. A registered professional engineer in Nebraska and Colorado, Mr. Patterson earned his B.S. and M.S. degrees in engineering from the University of Nebraska.

Nicholas Pinter is a professor in the Department of Geology and in the Environmental Resources and Policy Program at Southern Illinois University, Carbondale. His work is in the area of earth-surface processes, with a focus on fluvial geomorphology, flood hydrology, and floodplain management. His research and teaching also span other areas of surficial earth processes and their scientific and policy applications. Dr. Pinter's current projects include investigating the changes in morphology and flow dynamics of the Mississippi River system through the past century of river modification and management. A particular focus has been hydrologic, statistical, and modeling assessments of changes in flood occurrence and flood dynamics. Similar research is looking at comparable changes on other river systems, including a number of large navigable rivers in Europe. Dr. Pinter holds a B.A. degree from Cornell University, M.S. degree from The Pennsylvania State University, and Ph.D. degree from the University of California at Santa Barbara.

Sujoy Roy is an environmental engineer at Tetra Tech with extensive experience studying water quality and water supply impacts in large watersheds. His recent work involves the modeling of contaminants of drinking water concern in California's Central Valley as well as the development of a detailed master plan to manage land uses in the Mokelumne River watershed. Dr. Roy also led the development of a master plan to improve the water quality of the New and Alamo Rivers, specifically suspended solids, nutrients, and trace metals and organics. Dr. Roy provides support to the EPA for the development of nutrient standards in all surface waters in the states of California, Nevada, Arizona, and Hawaii. Past representative studies include the development of a model to predict the response of Chesapeake Bay to changing nutrient sources in the watershed and airshed, assessment of transport of chemicals on colloidal particles, evaluation of mercury fate and transport in terrestrial and aquatic ecosystems, experimental evaluation of PCB leaching from sludges, and modeling of transport of contaminants from former manufactured gas plant sites. Dr. Roy holds M.S. and Ph.D. degrees in civil and environmental engineering from Carnegie Mellon University and a B.Tech. degree in civil engineering from the Indian Institute of Technology, New Delhi, India.

Donald Scavia is Graham Family professor of sustainability, professor of natural resources and environment, professor of civil and environmental engineering, and director of the Graham Sustainability Institute at the University of Michigan. Prior to joining the Michigan faculty, he worked at the National Oceanic and Atmospheric Administration as Chief Scientist of the National Ocean Service and Director of the National Centers for Coastal Ocean Science and the Coastal Ocean Program. Dr. Scavia's research interests include the effects of natural and anthropogenic stresses on Great Lakes and marine ecosystems, with a focus on the use of models and integrated assessments in transferring knowledge to the decision-making process. He is principal investigator on three NOAA projects: two on coastal and Great Lakes hypoxia and ecological forecasting that focus on modeling the impacts of land-use changes, and one on climate adaptation in the Great Lakes region. Dr. Scavia earned his B.S. and M.S. degrees in environmental engineering from Rensselaer Polytechnic Institute and his Ph.D. degree in environmental engineering from the University of Michigan.

Sandra B. Zellmer is the Law Alumni Professor of Natural Resources Law at the University of Nebraska College of Law. She previously was a professor at the University of Toledo College of Law. She also served as a trial attorney in the Environment and Natural Resources Division of the U.S. Department of Justice, where she litigated public lands and wildlife issues for various federal agencies, including the National Forest Service, National Park Service, and Fish and Wildlife Service. She has practiced law at Faegre & Benson in Minneapolis, Minnesota, and clerked for the Honorable William W. Justice, U.S. District Court, Eastern District of Texas. Ms. Zellmer teaches and writes about natural resources, public lands, water conservation and use, and constitutional and environmental law. Ms. Zellmer received her LLM in environmental law from the George Washington University National Law Center, J.D. from the University of South Dakota School of Law, and B.S. degree from Morningside College.