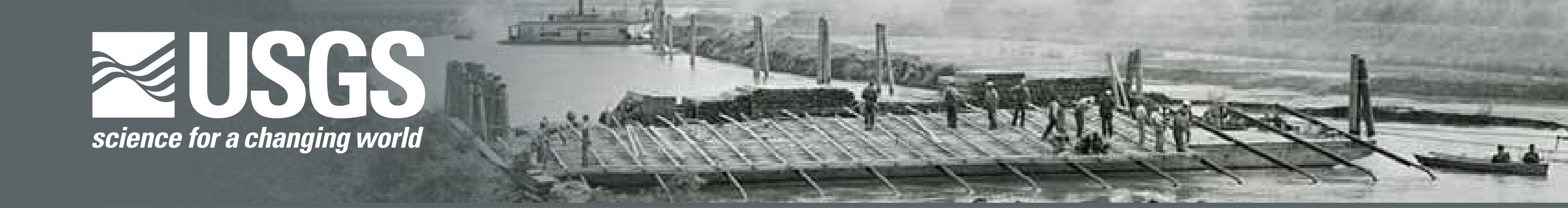

Prepared in cooperation with the U.S. Department of State

A Brief History and Summary of the Effects of River Engineering and Dams on the Mississippi River System and Delta

Circular 1375

U.S. Department of the Interior
U.S. Geological Survey

Cover. Construction of Gavins Point Dam, circa 1961 (source: U.S. Army Corps of Engineers).

A Brief History and Summary of the Effects of River Engineering and Dams on the Mississippi River System and Delta

By Jason S. Alexander, Richard C. Wilson, and W. Reed Green

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Contents

Figures

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
pound-force per square foot (lb/ft^2)	47.89	newton per square meter (N/m^2)
pound per foot-second (lb/ft-s)	14.59	newton per meter-second (N/m-s)
acre-feet (acre-ft)	8.11	hectare meter (ha-m)

SI to Inch/Pound

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6212	mile (mi)
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
newton per square meter (N/m^2)	0.1622	pound-force per square foot (lb/ft^2)
newton per meter-second (N/m-s)	0.0685	pound per foot-second (lb/ft-s)
hectare meter (ha-m)	0.1233	acre-feet (acre-ft)

Water year is defined as the 12-month period October 1 through September 30.

The water year is designated by the calendar year in which it ends.

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD29)

A kiloyear is equivalent to 1,000 years.

View of Lock and Dam 27, last navigation lock on the Mississippi River, oriented north; St. Louis, Missouri, is in the background (source: U.S. Army Corps of Engineers).

A Brief History and Summary of the Effects of River Engineering and Dams on the Mississippi River System and Delta

By Jason S. Alexander, Richard C. Wilson, and W. Reed Green

Abstract

The U.S. Geological Survey Forecast Mekong project is providing technical assistance and information to aid management decisions and build science capacity of institutions in the Mekong River Basin. A component of this effort is to produce a synthesis of the effects of dams and other engineering structures on large-river hydrology, sediment transport, geomorphology, ecology, water quality, and deltaic systems. The Mississippi River Basin (MRB) of the United States was used as the backdrop and context for this synthesis because it is a continental scale river system with a total annual water discharge proportional to the Mekong River, has been highly engineered over the past two centuries, and the effects of engineering have been widely studied and documented by scientists and engineers.

The MRB is controlled and regulated by dams and river-engineering structures. These modifications have resulted in multiple benefits including navigation, flood control, hydropower, bank stabilization, and recreation. Dams and other river-engineering structures in the MRB have afforded the United States substantial socioeconomic benefits; however, these benefits also have transformed the hydrologic, sediment transport, geomorphic, water-quality, and ecologic characteristics of the river and its delta. Large dams on the middle Missouri River have substantially reduced the magnitude of peak floods, increased base discharges, and reduced the overall variability of intraannual discharges. The extensive system of levees and wing dikes throughout the MRB, although providing protection from intermediate magnitude floods, have reduced overall channel capacity and increased flood stage by up to 4 meters for higher magnitude floods.

Prior to major river engineering, the estimated average annual sediment yield of the Mississippi River Basin was approximately 400 million metric tons. The construction of large main-channel reservoirs on the Missouri and Arkansas Rivers, sedimentation in dike fields, and protection of channel banks by revetments throughout the basin, have reduced the overall sediment yield of the MRB by more than 60 percent. The primary alterations to channel morphology by dams and other engineering projects have been (1) channel simplification and reduced dynamism; (2) lowering of channel-bed elevation; and (3) disconnection of the river channel from the flood plain, except during extreme flood events.

Freshwater discharge from the Mississippi River and its associated sediment and nutrient loads strongly influence the physical and biological components in the northern Gulf of Mexico. Ninety percent of the nitrogen load reaching the Gulf of Mexico is from nonpoint sources with about 60 percent coming from fertilizer and mineralized soil nitrogen. Much of the phosphorus is from animal manure from pasture and rangelands followed by fertilizer applied to corn and soybeans. Increased nutrient enrichment in the northern Gulf of Mexico has resulted in the degradation of water quality as more phytoplankton grow, which increases turbidity and depletes oxygen in the lower depths creating what is known as the “dead zone.” In 2002, the dead zone was 22,000 square kilometers (km^2), an area similar to the size of the State of Massachusetts.

Changes in the flow regime from engineered structures have had direct and indirect effects on the fish communities. The navigation pools in the upper Mississippi River have aged, and these overwintering habitats, which were created when the pools filled, have declined as sedimentation reduces water depth. Reproduction of paddlefish may have been adversely affected by dams, which impede access to suitable spawning habitats. Fishes that inhabit swift-current habitats in the unimpounded lower Mississippi River have not declined as much as in the upper Mississippi River. The decline of the pallid sturgeon may be attributable to channelization of the Missouri River above St. Louis, Missouri. The Missouri River supports a rich fish community and remains relatively intact. Nevertheless, the widespread and long history of human intervention in river discharge has contributed to the declines of about 25 percent of the species.

The Mississippi River Delta Plain is built from six delta complexes composed of a massive area of coastal wetlands that support the largest commercial fishery in the conterminous United States. Since the early 20th century, approximately 4,900 km^2 of coastal lands have been lost in Louisiana. One of the primary mechanisms of wetland loss on the Plaquemines-Balize complex is believed to be the disconnection of the river distributary network from the delta plain by the massive system of levees on the delta top, which prevent overbank flooding and replenishment of the delta top by sediment and nutrient deliveries. Efforts by Federal and State agencies to conserve and restore the Mississippi River Delta Plain began over three decades ago and have accelerated over the past decade. Regardless of these efforts, however, land losses are expected to continue because the reduced upstream sediment supplies are not sufficient to keep up with the projected depositional space being created by the combined forces of delta plain subsidence and global sea-level rise.

Introduction

Large rivers are important for economies and global ecosystems. For economies, a large river is an important source of transportation, power generation, and water supply, which are key elements of infrastructure, industry, and security and, therefore, are cornerstones for economic development and stability. Large-river ecosystems, on the other hand, are some of the most biodiverse on earth and provide natural, renewable sources of food for industrialized and emerging economies. Large rivers also are primary components of global biogeochemical cycling because they integrate and deliver the chemical and sedimentary loads of landscapes to major deltas and continental shelves, which are also global centers of biodiversity, and provide important sources of a secure food supply (Stanley and Warne, 1997; Day and others, 2007b).

The importance of large rivers to societies is easily recognizable because many modern and ancient population centers are located along the banks of large rivers, tributary streams, and deltas. Engineering works typically are constructed along large-river systems to increase the ease of transportation of goods, produce reliable base-level energy production, secure or increase water supplies, and mitigate or control flood hazards. Although engineering in river systems has economic benefits to society, these benefits often come with ecologic consequences that, if not fully considered, may eventually counterbalance some economic benefits or conflict with modern societal values (Schmidt and others, 1998). In recent decades, industrialized nations such as the United States, members of the European Union, and Australia have recognized these ecologic consequences and have been making expensive and politically contentious attempts to rehabilitate riverine ecosystems, often with the goal of preserving or recovering animal species pushed to the brink of extinction or improving the quality of municipal water supplies (Bernhardt and others, 2005; Lake and others, 2007). Over the past two decades, societal pressures to rehabilitate riverine ecosystems has advanced scientific understanding of the effects of alterations on river hydrology and sediment regimes on river channels, physical habitat, and water quality.

The U.S. Geological Survey Forecast Mekong project is providing technical assistance and information to aid management decisions and build science capacity of institutions in the Mekong River Basin in the nations of Thailand, Laos, Cambodia, and Vietnam (Turnipseed, 2011). A component of this effort is to produce a synthesis of the effects of dams and other engineering structures on large-river hydrology, sediment transport, geomorphology, ecology, water quality, and deltaic systems. The Mississippi River Basin (MRB) of the United States was used as the backdrop and context for this synthesis because it is a continental-scale river system with a total annual water discharges similar to the Mekong River, has been highly engineered over the past two centuries, and the effects of engineering have been widely studied and documented by scientists and engineers.

Purpose and Scope

The purpose of this report is to summarize the effects of dams and other engineering projects (in particular levees, dikes, and revetments), on the hydrology, sediment transport, geomorphology, ecology, water quality, and delta on the Mississippi River system. This report provides a synopsis of existing scientific literature and other agency reports organized into series of summaries that the authors deem critical to understanding how and, to the extent possible, why the Mississippi River and its delta have been changed by engineering activities. This report is not intended to provide new analyses or insights not previously published. This synopsis is not spatially comprehensive, in part because current scientific investigations have not quantified effects on every river mile within the basin, but also because the effects of particular engineering activities can generally be constrained by magnitude to particular parts of the river basin. For example, engineering on the Missouri River is widely suspected to have substantially affected the natural sediment supply delivered to the Mississippi River Delta Plain

(National Research Council, 2011) and, therefore, most of the scientific analyses of sediment transport have been focused on this tributary. No analyses of the potential effects of planned developments in the Mekong Basin are provided.

Description of the Mississippi River Basin

The MRB spans parts of 31 States in the United States and 2 Provinces in Canada (fig. 1). The MRB covers 41 percent of the conterminous United States and totals 3,224,600 square kilometers (km^2). The Mississippi River extends approximately 3,770 kilometers (km) from its headwaters at Lake Itasca, Minnesota, to the Gulf of Mexico (Kammerer, 1990) and, in combination with its longest tributary the Missouri River, is one of the longest rivers in the world (Leopold, 1994). The MRB is bound on the west by the Rocky Mountain Belt, on the north-central by the West Lake section of the Interior Plains, and on the east by the Appalachian Mountains (Fenneman, 1928). Because of the width of its span as well as its geographic position, the MRB is physiographically and ecologically diverse, incorporating 24 ecoregions along its course to the Gulf of Mexico (Omernik, 1987; Mac and others, 1998; Ricketts and others, 1999). Primary MRB tributary basins are the Ohio River, the Missouri River, the Arkansas River, and the Red River.

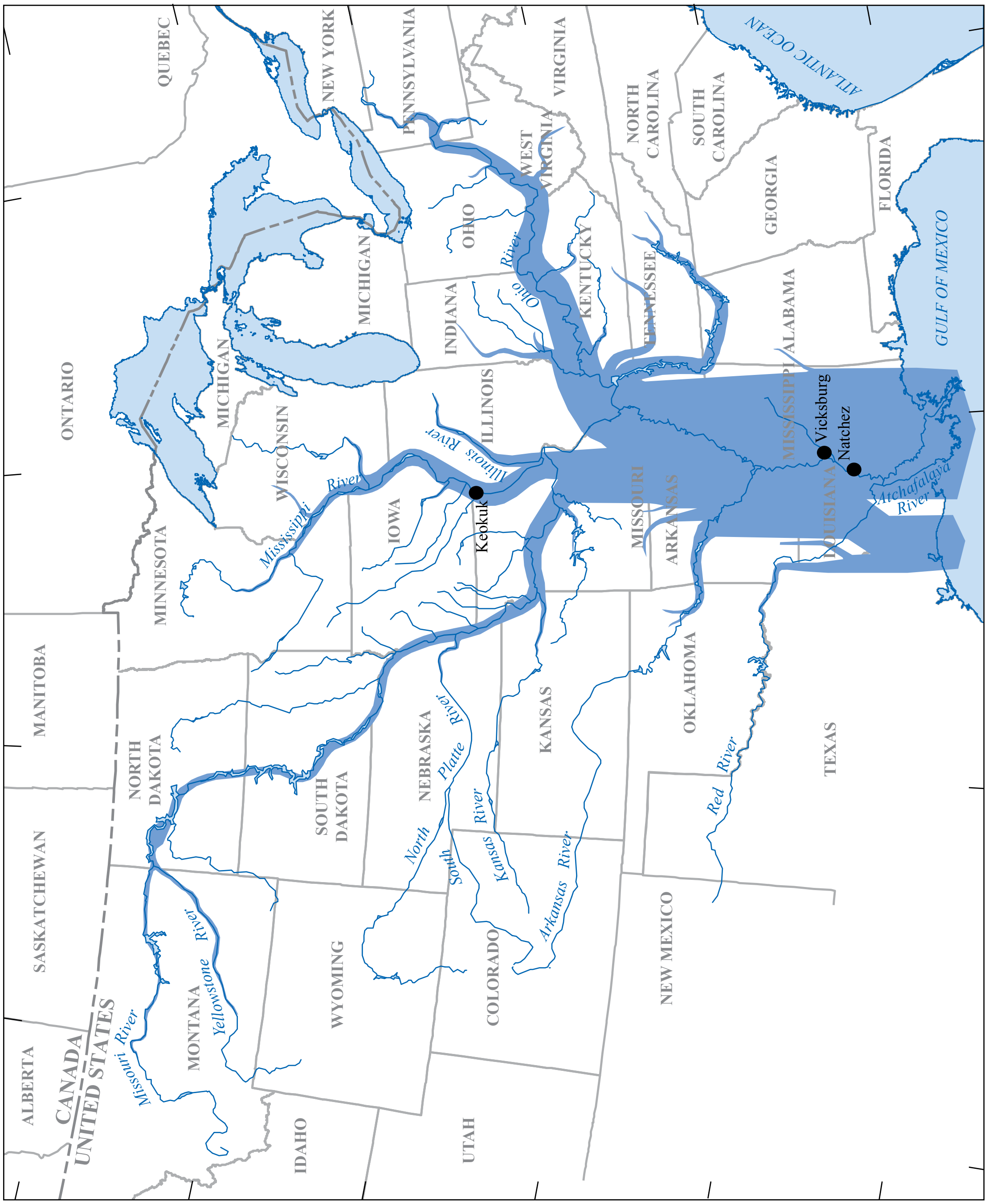
For the purposes of this report, the terms "upper," "middle," and "lower" are used in reference to the reaches of the Mississippi River upstream from St. Louis, Mo., from St. Louis to the confluence with the Ohio River, and from the confluence of the Ohio River to the Gulf of Mexico, respectively. In reference to the Missouri River, the terms "upper," "middle," and "lower" correspond to the reaches of the Missouri River upstream from Fort Peck Lake, Montana, between Fort Peck Lake and Gavins Point Dam, South Dakota, and downstream from Gavins Point Dam, respectively (fig. 1).

The Mississippi River, in combination with its largest distributary the Atchafalaya River, discharges an annual average of 580 km^3 of water into the Gulf of Mexico (Meade and others, 1995; Brown and others, 2005). About half of the total annual discharge is contributed by the Ohio River alone, which drains the more humid regions of the basin but only constitutes one-sixth of the total MRB area (Meade, 1995). Alternatively, the Missouri River drains approximately 43 percent of the MRB but contributes only about 12 percent of the total annual water discharge (fig. 2). In the MRB, the primary sources of sediment and water are decoupled. The primary source of sediment in the basin is the Missouri River, which drains large parts of the Great Plains region of North America (fig. 3). The Great Plains region, which includes the Missouri, Arkansas, and Red River Basins, produces proportionally larger sediment discharges because of a combination of a semiarid climate, resulting in a lower density of vegetated land cover, yet enough precipitation to mobilize substantial masses of sediments into streams (Langbein and Schumm, 1958).

Dams and river engineering in the MRB have afforded the United States substantial socioeconomic benefits allowing for agricultural expansion into the nutrient-rich soils of the valley bottomlands adjacent to the river (Pinter, 2005), water supplies for irrigated agriculture and municipalities, maintenance of a deep navigation channel for shipping, base-level power generation, flood protection for communities adjacent to the river, and a resource for material extraction. Over the past 60 years, parts of the MRB also have emerged as important recreational resources, which have become a more substantial component of the economic base in rural parts of the river basin, particularly in areas surrounding reservoirs (Hesse, 1995).

Although the economic benefits of dams and engineering projects in the MRB have undoubtedly been substantial, these benefits also have come with socioeconomic and ecologic costs. The construction of the massive system of reservoirs between 1932 and 1962 in the Missouri River Basin required displacement of thousands of people, including many Native Americans, inhabiting the river bottoms (Weist, 1995; Sims, 2001). Reservoir sedimentation along the Missouri River has induced sedimentation and elevated groundwater levels upstream from reservoirs, severely enough in some locations that the U.S. Army Corps of Engineers (USACE) has permanently moved entire communities to higher ground. The channelization of the Missouri and Mississippi Rivers has come at the expense of wetland and riparian habitats and reduced the water and nutrient storage capacity of the bottomlands, magnified flood stages, and added to the difficult problem of hypoxia in the Gulf of Mexico (Rabalais and Turner, 2001; Pinter and Heine, 2005). Additionally, besides having substantial ecologic consequences, loss of wetlands off the coasts of Louisiana and Mississippi—which has been partly attributed to human-induced disconnection of the Mississippi River Delta Plain from the Mississippi River distributary network as well as reductions in sediment loads from upstream reservoir construction—has reduced the natural wave attenuation capacity of the coastal shelf, increasing the risk of flood hazard from storm surge in nearby coastal communities (Day and others, 2007a).

Figure 1. Mississippi River Basin, primary tributaries, large main-channel dams, and selected cities along main-stem channels.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1990
Albers Equal-Area Conic projection
North American Datum of 1983

Figure 2. Mean annual water discharges of the main-channel and primary tributaries to the Mississippi River (modified from Meade and Moody, 2010).

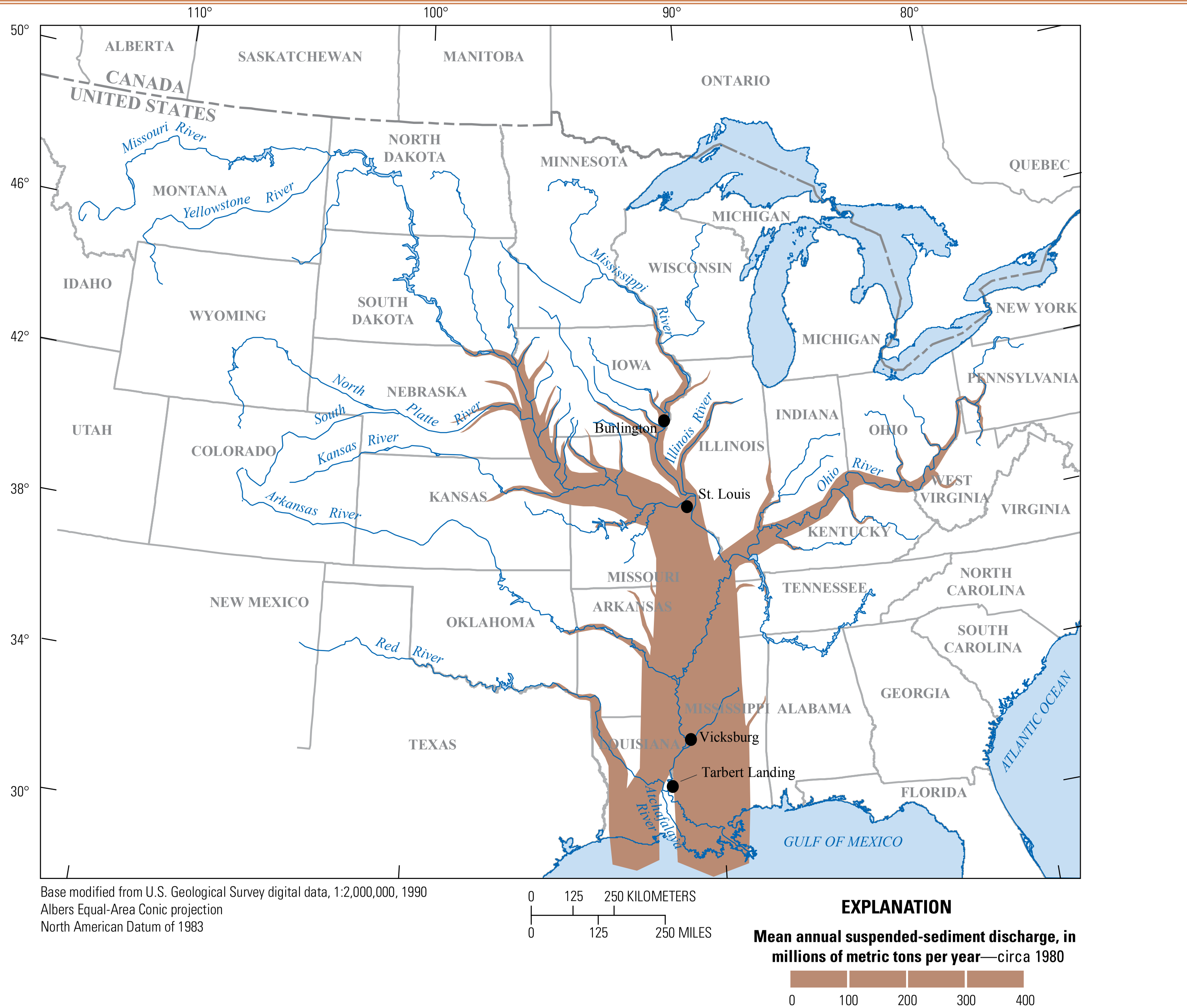


Figure 3. Postdevelopment mean annual suspended-sediment discharge along the Mississippi River and major tributaries, circa 1980 (modified from Meade and Moody, 2010).

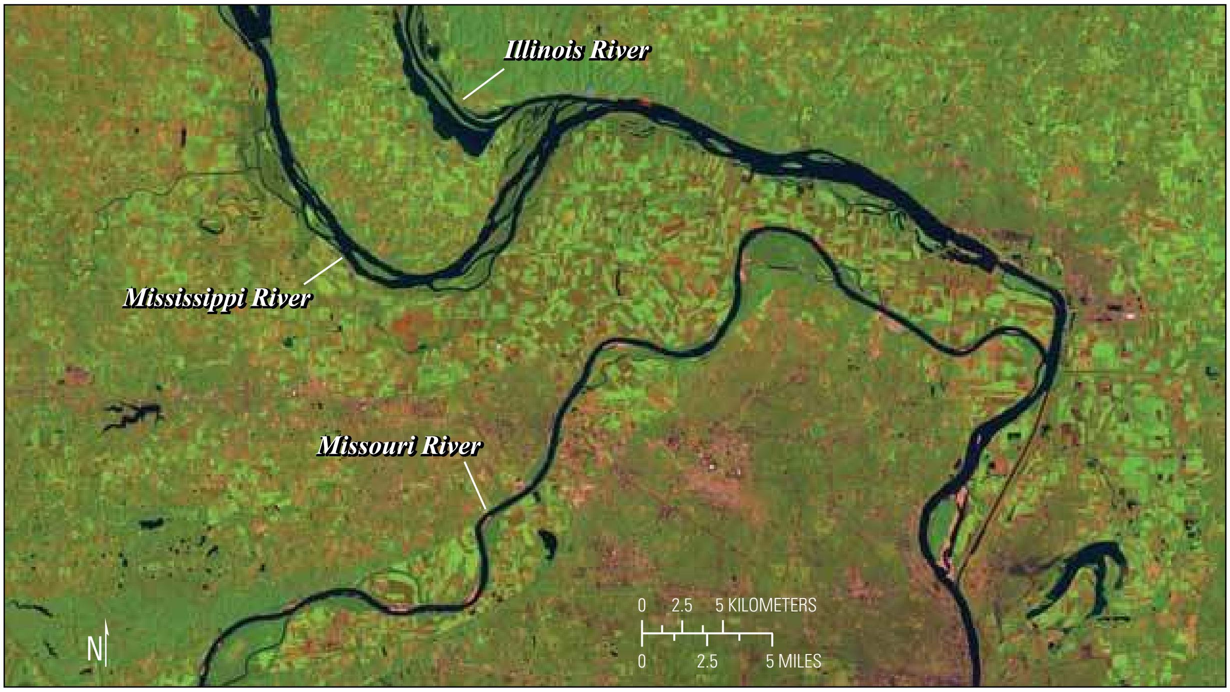
A Brief History of River Engineering in the Mississippi River Basin

The Mississippi River and many of its tributaries have served as a vital transport route for the United States. In 1811, the first steamboat traveled from Pittsburg, Pennsylvania, down the Ohio River and then the Mississippi River to New Orleans (Evans, 1907; Dohan, 1981); in 1819, the first steamboat traveled the Missouri River (Ferrell, 1993). By 1867, the Missouri River had been cleared of snags allowing steamboats to navigate as far upstream as Fort Benton, Montana (fig. 1) (U.S. Army Corps of Engineers, 1984). The MRB also has been the source of devastating floods. The Great Mississippi River Flood of 1927, estimated at 66,545 cubic meters per second (m^3/s) at Red River Landing, approximately 97 km below Natchez, Mississippi, inundated an estimated 69,930 km^2 of land in seven states (Barry, 1997). The 1927 flood killed 246 people, and over 700,000 people were forced to evacuate (fig. 4). Total property damage from the flood was estimated at $400 million, exceeding the losses of all previous Mississippi River floods combined (U.S. Army Corps of Engineers, 2002).

In 1993, the costliest flood in the history of the United States occurred in the upper MRB, later deemed the "Great Flood of 1993" (Johnson and others, 2004). The flood was the result of widespread and persistent precipitation in the Midwestern United States from June through August of 1993. The discharge of the Mississippi River during the peak of the flood was estimated to be a record 30,582 m^3/s at St. Louis, Missouri (Johnson and others, 2004), and also posted a record flood stage of 15.1 meters (m) on August 1. The flooding (fig. 5) caused widespread levee failures, damaged transportation systems and municipal infrastructure, destroyed more than 50,000 homes, and killed at least 48 people (Johnson and others, 2004). Economic damage from the Great Flood of 1993 approached $20 billion (Johnson and others, 2004).

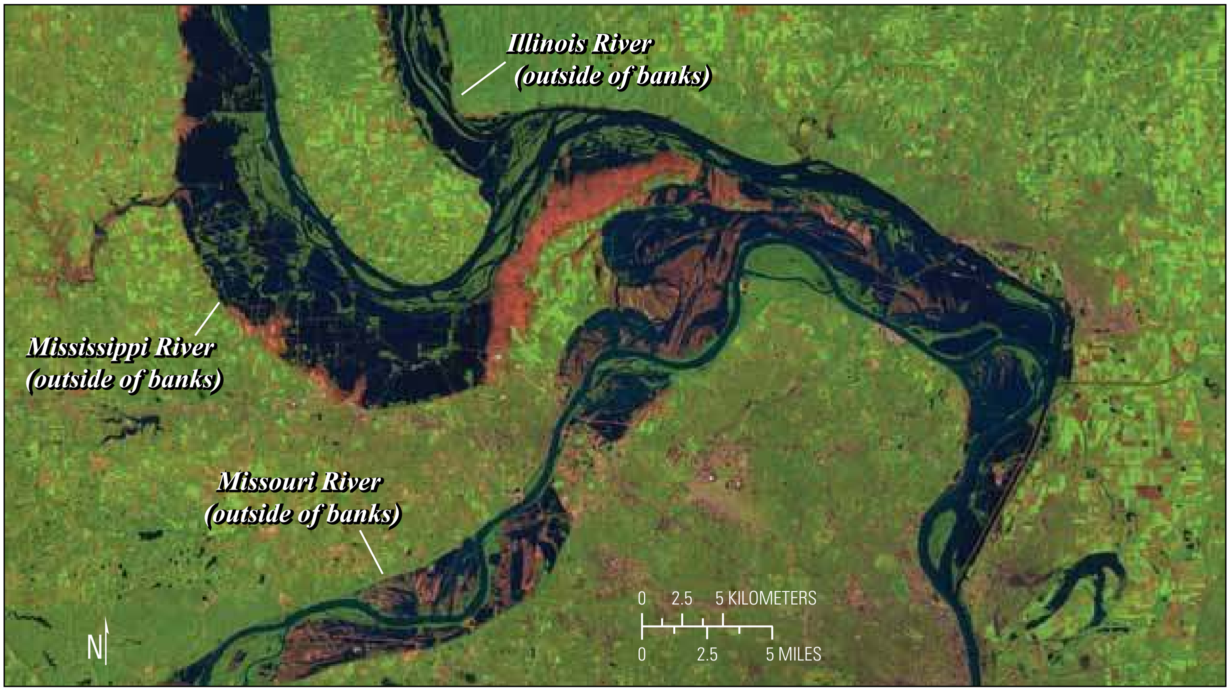
Figure 4. American family near their flooded farmstead during the Great Mississippi River Flood of 1927 (source: U.S. Army Corps of Engineers).

***A.* August 14, 1991**—Rivers within banks



Satellite image courtesy of Jesse Allen, National Aeronautics and Space Administration Earth Observatory and U.S. Geological Survey Earth Resources Observation Systems Data Center

***B.* August 19, 1993**—Rivers at peak of Great Flood of 1993



Satellite image courtesy of Jesse Allen, National Aeronautics and Space Administration Earth Observatory and U.S. Geological Survey Earth Resources Observation Systems Data Center

Figure 5. Images of the confluence area of the Mississippi, Illinois, and Missouri Rivers near St. Louis, Missouri.

River Engineering

The MRB is controlled and regulated by dams and other river engineering structures. These modifications, some of which began in the early 1800s (U.S. Army Corps of Engineers, 2002), have resulted in multiple benefits including navigation, flood control, hydropower, bank stabilization, and recreation. The Mississippi River and its tributaries serve as major transportation routes, and the natural channel and hydrology did not provide the stable, uniform, consistently deeper channel that was needed for efficient navigation of the river. Channelizing and stabilizing the Mississippi and Missouri Rivers was a monumental task, requiring extensive modifications to stabilize the freely meandering river channel and banks and to create a self-scouring channel for navigation by reducing channel width and complexity. Flood control in the MRB is accomplished through a complex combination of levees to confine and separate the river channel from the flood plain, engineered floodways to reduce flood stages near critical infrastructure, channel straightening to increase the conveyance capacity of the channel, and the construction of dams on the tributaries to attenuate flood peaks and store irrigation water.

Clearing of Snags and Obstructions

The first major MRB modifications consisted of widespread clearing of snags and obstructions to increase the ease and safety of river navigation. Downed trees and rocks snagged and sank keelboats and steamboats, whereas sandbars and rapids slowed or prevented the upstream movement of boats (fig. 6). The Missouri River was known to be particularly treacherous for steamboat navigation because of the numerous snags caused by fallen trees and branches (Bureau of Reclamation, 2011). The USACE began removing snags and dredging the main channel of the Mississippi River in the early 1800s, and in the main channel of the lower Missouri River by 1832 (U.S. Army Corps of Engineers, 1984). The problem of snags was not limited to the Missouri River. The 1882 Annual Report of the Secretary of War states, "The snag boat O.G. Wagner removed 834 river snags and 380 shoreline snags from the Red River in one week" (U.S. War Department, 1882). The result of the clearing of snags and obstructions made navigation easier and safer; however, the modifications were only temporary because annual channel migration caused substantial bank erosion, and continuously fed the channel with additional trees from the banks. Thus, snag clearing often was repeated after each high-water event (U.S. Army Corps of Engineers, 1980). River engineering projects such as channel straightening, dike construction, and revetments reduced the number of snags and obstructions, but channel dredging continues today.

Figure 6. A steamboat collision with snag on Mississippi River (source: Mississippi River Commission).

Channel Straightening and Cutoffs

The meandering rivers of the MRB have been extensively modified by channel straightening and shortened by cutoffs of river bends. Meandering "loops" are created as the river erodes the outside of a river bend and deposits sediment on the inside of the curve. This process causes the channel to migrate across the valley bottom and occurs because the velocity of the river is higher on the outside of the curve and slower on the inside of the curve (Dietrich and others, 1979). As the process of channel migration continues, the bend in the river eventually becomes larger and more circular, the length of the channel increases, and channel slope decreases. If allowed to persist, the large-meander loops would eventually naturally "cut off" during a high discharge event, disconnecting the meander loop from the channel, leaving behind an oxbow lake, and substantially shorten and steepen the channel.

Construction of long radius channels that reduce the overall curvature of river bends, in combination with engineered cutoffs of large meanders, have modified the channel alignment and made the river more efficient for navigation. River cutoffs were designed to ensure that the artificial channel shape, size, slope, and alignment were adequate to allow the cutoff to evolve naturally with the discharge of the river (Morris and Wiggert, 1972). The result is a shorter river, with higher average velocities and self-scouring channels. Channelization and cutoffs in the lower Missouri River shortened the river length by approximately 116 km. Between 1929 and 1942, the USACE constructed 14 cutoffs in the lower Mississippi River between Memphis, Tennessee, and Red River Landing, Louisiana. The engineered cutoffs, in combination with two natural cutoffs, resulted in a net shortening of the river of approximately 235 km (Winkley, 1977).

Revetments

Revetments are used extensively throughout the MRB to stabilize river banks, prevent bank erosion, and reduce the tendency of the river to migrate across the flood plain. Revetments cover the bank from the top high water-surface elevation and extend below the water surface to the submerged toe of the bank. Revetments are constructed by using a variety of techniques and materials. Early revetments were constructed of willow fascine or lumber framework mattresses wired together to form a protective structure and then placed on the graded sloped bank (Morris and Wiggert, 1972). Mattresses were backfilled with sediment and armored with rock riprap (fig. 7). The 1920 Annual Report of the Chief of Engineers (U.S. War Department, 1920) reported "for the Missouri River bank protection project at Vermillion, South Dakota standard permeable dikes with foot mattresses and revetment of continuous woven-brush mattresses with rock paved upper banks were used extensively at revetment works." Today, common forms of revetments are articulated concrete block mattresses and trench-fill revetments. Typical concrete block mattresses used on the lower Mississippi River measure 1.2 m in width and 7.6 m in length. The individual mats are woven together with steel wire and placed on the bank by barge (U.S. Army Corps of Engineers, 2011). Trench-fill revetments are constructed by placing riprap along the margin of a bank, allowing the river to erode the toe of the bank, creating a trench, and allowing the riprap to fall into the trench creating the protective structure.

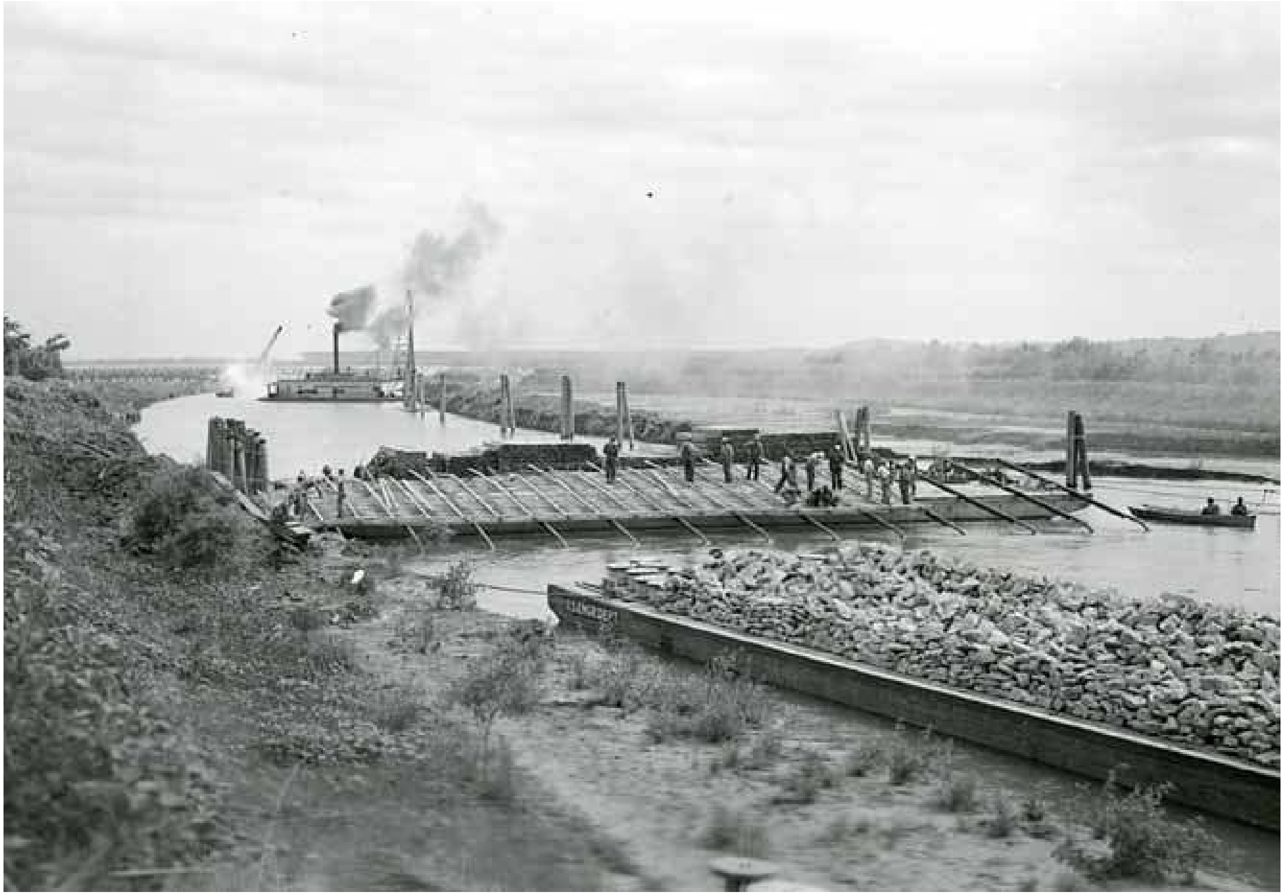


Figure 7. Construction of Missouri River revetment, June 2, 1938 (source: U.S. Army Corps of Engineers).

Dikes

Dikes are used for river-flow contraction and training and alignment of the wide meandering river channels of the MRB. Dikes extend from the riverbank into the river channel, perpendicular to the direction of flow. The dike structure directs the river flow toward the center of the channel, increasing the velocity in the channel midsection, causing scouring of the bed sediment, and resulting in a deeper channel. Dikes take many sizes and alignments and consequently have been called by a variety of names including spur dikes, spur dams, wing dikes, wing dams, groins (or groynes), contracting dikes, transverse dikes, cross dikes, cross dams, jetties, longitudinal dikes, L-head dikes, and vane dikes (U.S. Army Corps of Engineers, 1980). Dikes have two primary forms: impermeable and permeable. Impermeable dikes are armored structures constructed of riprap, concrete, rubble, or other hard materials and are the most commonly used dike in the MRB. Permeable dikes such as the pile-clump dike are constructed of timber piles, woody debris, or trees woven together. Permeable dikes reduce the velocity of the surrounding flow field, allowing sediment to naturally deposit and fill within the voids of the structure (fig. 8.). Permeable dikes are most effective in rivers with heavy sediment loads, such as the Missouri River (Linsley and Franzini, 1979). Although fundamentally different in design, impermeable and permeable dikes have been used to successfully create and maintain the navigation channels throughout the MRB.

Levees and Floodways

Levees and floodways have been constructed extensively for flood protection in the MRB. In 1920, the Annual Report of the Chief of Engineers (U.S. War Department, 1920) reported 2,700 km of levees, totaling 276,694,000 m^3 of material, between Rock Island, Illinois and Head of Passes, La. Today, the lower MRB alone has over 5,630 km of levees (Mississippi River Commission, 2011). The levee is essentially a dam placed on the river bank parallel to the channel to prevent flooding during times of high discharge stages (fig. 9). Unlike a dam, the levee is expected to be subjected to high water only for a few days to several weeks at a time (U.S. Army Corps of Engineers, 2000). Most levees in the MRB are constructed of compacted sediment. By design, the least permeable sediments, such as clays, are placed in the riverside of the structure. Levee heights are variable and are designed on the basis of a combination of factors including the estimated flood stage, types of land uses and structures behind the levee, material type, foundation, and the availability of land for construction. The levees in the MRB generally have broad bases and gentle side slopes, particularly on the landward side (U.S. Army Corps of Engineers, 2000).

Floodways are used to supplement and enhance the flood protection capabilities of the system of levees in the MRB. Floodways are designed to carry and redirect excess flood discharges around cities to less densely populated areas, often agricultural areas along the valley bottomland. When opened, the floodways reduce the discharge in the main river channel, thereby reducing flood stage, allowing high water to bypass more densely populated areas, and alleviating stress on the levee systems (Winkley, 1994; Smith and Winkley, 1996). In the lower MRB, three major floodways have been constructed in Louisiana at the Atchafalaya River, the Morganza Floodway, and the West Atchafalaya Floodway, and one in Missouri at the Birds Point-New Madrid floodway.

Dams and Reservoirs

Dams are used throughout the MRB to stabilize, harness, and regulate the discharges of rivers. The MRB has thousands of single-purpose and multiple-purpose dams and navigation locks that provide flow regulation for navigation, flood control, hydropower, water supply, irrigation, fish and wildlife habitat, water-quality control, and recreation (U.S. Army Corps of Engineers, 2006). Of note, the middle and lower sections of the Mississippi River are not impounded by any main-channel dams; however, all of their major tributaries have impoundments.

A. **September 1934**

B. **November 1934**

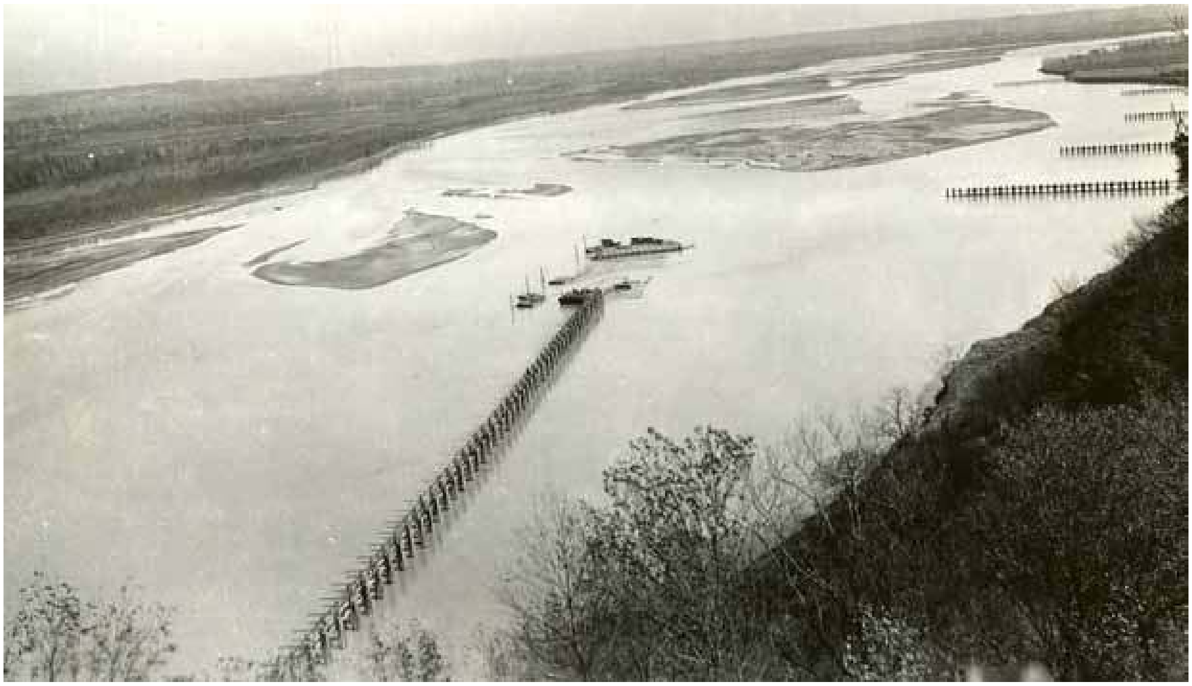


Figure 8. The siltation of a dike system, Indian Cave Bend, Missouri River (source: U.S. Army Corps of Engineers, Omaha District).

C. **August 1936**

D. **May 1946**

Figure 8. The siltation of a dike system, Indian Cave Bend, Missouri River (source: U.S. Army Corps of Engineers, Omaha District).—Continued

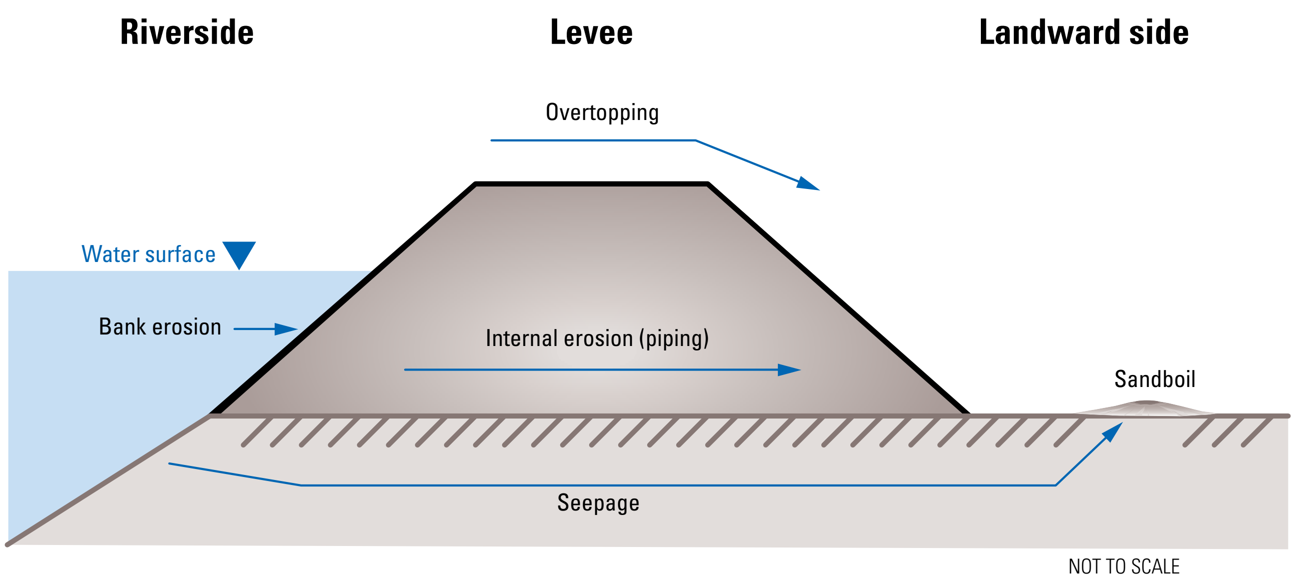


Figure 9. Levee design and failure mechanisms.

The Missouri River Mainstem Reservoir System located in the northern High Plains is an example of multiple-purpose dams and their operation as an integrated system. Five of the six massive earthen main-stem dams were authorized by the Flood Control Act of 1944, commonly referred to as the "Pick-Sloan Act." The six main-stem dams were constructed from 1933 to 1964 (fig. 10), and the system of dams now composes the largest reservoir system in the United States (U.S. Army Corps of Engineers, 2004). The Missouri Mainstem Reservoir System is primarily operated by the USACE, but the Bureau of Reclamation also operates other reservoirs within the system. The main-stem system contains about 90.5 million hectare-meters (ha-m) of storage capacity and 404,700 ha of surface area and constitutes over 52 percent of the total storage in the Missouri River Basin (U.S. Army Corps of Engineers, 2006). Over 71 percent of the capacity of the Federal hydroelectric power system is generated by the main-stem system. The main-stem system provides flow for navigation and flood protection for over 810,000 ha in the flood plain of the Missouri River.

Several series of locks and dams in the MRB have helped to create an inland navigational waterway that extends south to north from the Gulf of Mexico to Minnesota and east to west from West Virginia to Iowa. Navigational locks and dams have been built on the upper Mississippi River, Ohio River, and Arkansas–Red Rivers but not on the lower Mississippi River or Missouri River. Navigation dams are similar to other dams in that their intended purpose is to impound water; however, navigation dams are designed to maintain the water surface upstream from the dam and, thereby, provide sufficient depth

Figure 10. Construction of Gavins Point Dam, circa 1961 (source: U.S. Army Corps of Engineers).

for the navigation of boats and barges (fig. 11). The passage of vessels between the upper and lower water-surface levels is accomplished by a navigation lock. In 1930, the U.S. Congress authorized the construction of a 9-foot-deep and 400-foot-wide navigation channel on the upper Mississippi River from Minneapolis downstream to the confluence with the Missouri River. These structures were built during the 1930s and 1940s (with the exception of the Keokuk power dam that was constructed in 1913) and resulted in a total of 29 locks and dams in the upper MRB. At least partially as a result of the system of navigation locks and dams, waterborne commerce has increased on the Mississippi River from 30 million tons in 1940 to nearly 400 million tons in 2011 (Mississippi River Commission, 2011). Currently, there are 21 navigation locks and dams on the main stem of the Ohio River (U.S. Army Corps of Engineers, 2012a), 18 on the main stems of the Arkansas and White Rivers (U.S. Army Corps of Engineers, 2012b), and 5 on the Red River (U.S. Army Corps of Engineers, 2012c). The U.S. Congress authorized the Missouri River navigation channel from St. Louis, Mo., to Kansas City, Mo., in 1910 and authorized the extension of the navigation channel to Sioux City in 1927. The Rivers and Harbors Act of 1945 authorized a 9-foot-deep and 300-foot-wide channel in the lower Missouri River (U.S. Army Corps of Engineers, 2006). Although flow for navigation in the lower Missouri River is regulated by the upstream system of reservoirs, the navigation channel of the lower Missouri River has no system of dams with navigation locks.

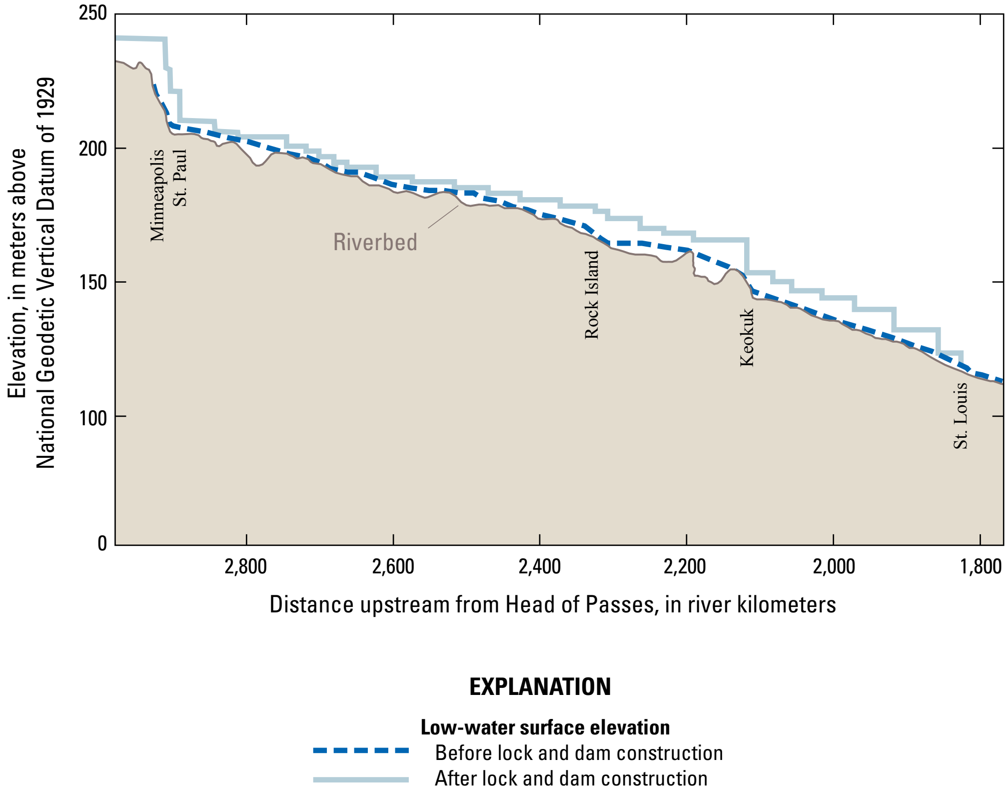


Figure 11. Low-water surface elevation profiles on the upper Mississippi River before and after construction of navigation locks and dams (modified from Meade, 1995).

River Management

The Mississippi River is managed by the Mississippi River Commission (MRC), which was created by an Act of the U.S. Congress, on June 28, 1879 (Camillo and Pearcy, 2004). The MRC is responsible for developing plans to improve the condition of the Mississippi River, foster navigation, promote commerce, and prevent destructive floods. The MRC is comprised of three generals from the USACE, one member from the National Oceanic and Atmospheric Administration, and three civilian members. The responsibilities of the MRC include the recommendation of policy, flood control, navigation, and environmental projects on the Mississippi River. The MRC also is responsible for the study and reporting on needed system modifications and for conducting inspections and public hearings. The work of the MRC is implemented by six USACE districts (St. Paul, Minnesota; Rock Island, Illinois; St. Louis, Mo.; Memphis, Tenn.; Vicksburg, Miss.; and New Orleans, Louisiana) (Camillo and Pearcy, 2004). The original operating procedure of the MRC for flood control was a "levees-only" approach, but the Great Mississippi River Flood of 1927 forced the MRC to reevaluate the plan for the lower Mississippi River (Barry, 1997). The U.S. Congress approved the Flood Control Act of 1928, and the MRC implemented a plan that changed the flood control approach to a comprehensive system that incorporates the use of floodways, reservoirs, spillways, cutoffs, and levees, while still improving and promoting the inland waterway.

The USACE in conjunction with other government agencies manages the Missouri River primarily by the Missouri River Master Manual (U.S. Army Corps of Engineers, 2006). The Master Manual was developed for operation of the Missouri River Mainstem Reservoir System. Because the extent and storage capacity of the main-stem reservoirs is larger than all the other tributary reservoir projects in the basin, the Master Manual integrates the operation of the system and tributary reservoirs into one comprehensive plan. The Master Manual provides guidance on implementing the authorized purposes of the Pick-Sloan Act including navigation, flood control, hydropower, water supply, irrigation, fish and wildlife, water quality, and recreation. The U.S. Congress did not assign priorities to these purposes. Instead, the USACE, in consultation with affected interests and other agencies, balances these functions to obtain the optimum development and use of the water resources of the Missouri River Basin to best serve the public (U.S. Army Corps of Engineers, 2006). The Master Manual is implemented by the Missouri River Mainstem Reservoir System Current Water Control Plan (CWCP). The CWCP delineates operational objectives during periods of drought, flood, and normal runoff conditions. The USACE adjusts the CWCP as conditions change to meet the operational objectives of the authorized purposes. The six main-stem reservoirs are divided into separate zones that dedicate the 9.0 million ha-m storage volume for the different authorized purposes. The top 6 percent of the storage volume is the exclusive flood-control zone; 16 percent is the annual flood-control and multiple-use zone or the normal operating zone; 53 percent is the carryover multiple-use zone for irrigation, navigation, power production, water supply, recreation, and fish and wildlife; and 24 percent is the permanent pool zone (fig. 12). The main-stem system is managed by the Missouri River Reservoir Control Center (RCC). The RCC was created in 1953 and controls the entire system from one central location (Ferrell, 1993).

A Summary of the Effects of River Engineering and Dams on the Mississippi River System and Delta

Large-river systems are extremely complex in both time and space. Over time, rivers respond to natural stressors, primarily climate, and adjust their geometries (channel size and shape) within the constraints of local geological controls. A river system in a deep bedrock canyon (for example, Colorado River in Grand Canyon) has limited capacity to adjust its horizontal position over short time periods, whereas a river in a wide alluvial valley (the Mississippi River downstream from the Ohio River) may shift its horizontal position annually. Over space, a large river will traverse a variety of landscapes, with local and regional geologic, climatic, and biologic changes that influence the geometry and hydraulics of the channel and flood plain. Engineering and modification of river systems are superimposed on this natural complexity, and the effects of individual engineering projects typically take many decades to run their course, often in parallel to a host of other engineering activities and changes in land use (Williams and Wolman, 1984).

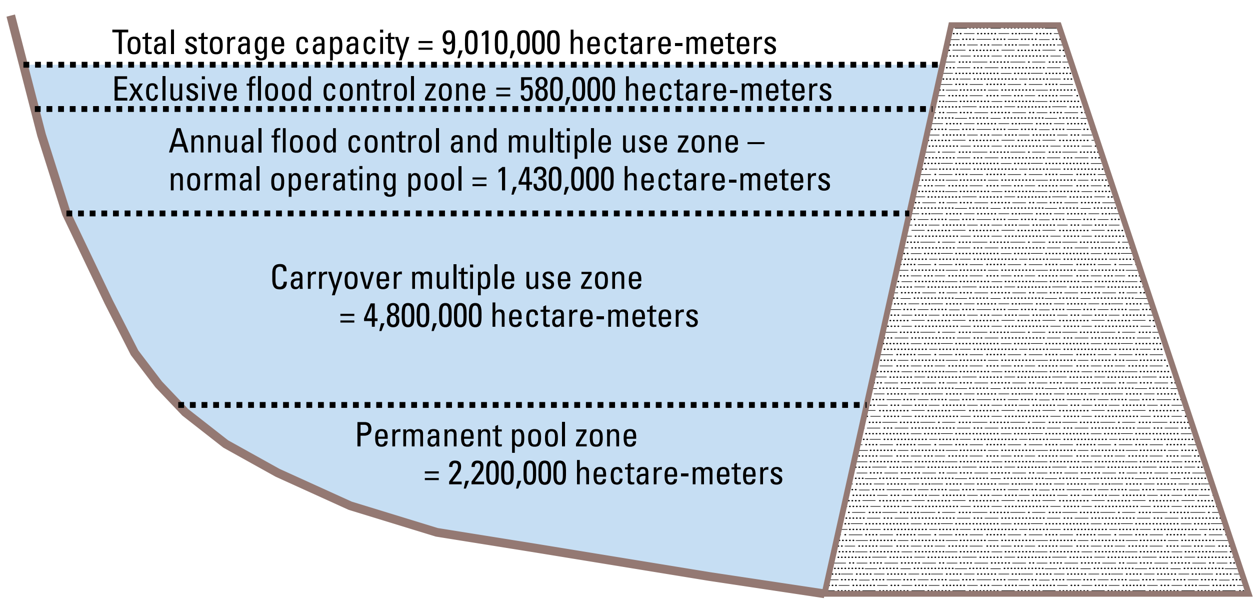


Figure 12. Storage capacity and designated uses of water in the main-stem reservoir system in the Missouri River.

The combination of natural spatial and temporal complexity, prolonged response times, number of engineering activities, and limited datasets confounds the determination of clear and direct cause-and-effect relations, such as those revealed through controlled experiments in a laboratory setting. Instead, geoscientists must use a combination of geologic and engineering theory, field investigations, historical accounts, and qualitative and quantitative data from varying sources and of varying quality to infer or interpret how a river system has responded to human influences. One of the primary difficulties is the fact that predevelopment datasets are typically limited in quantity, spatial and temporal extent, and quality and, therefore, an accurate characterization of a reference or "control" condition is difficult. In the United States, the host of writings dating back to Spanish missionaries through government-sponsored scientific explorations of the western territories in the 19th century provides some account of the predevelopment condition of the land and river valleys. Although the predevelopment condition of a river was affected to some extent by the activities of native peoples, these early accounts often are used as the reference condition when assessing human-induced changes to river systems (Moody and others, 2003).

Although the summaries of the effects of dams and engineering projects in this report are divided into individual physical and biological components of the river system, in reality, the components work in a systematic fashion through a complex series of interactions and feedback loops, which have developed over the geologic history of the river. Many of these interactions and feedback loops are still poorly understood by the scientific community. The summaries are a simplification of the system, intended to distill the effects of the dams and engineering structures into the most completely known and most clearly documented effects today.

Effects on Hydrology

A. Although main-channel dams are distributed throughout primary tributaries of the MRB, the regions with the most intensively altered hydrology are reaches of the middle and lower Missouri River. In the middle Missouri River, most of the river is now a system of large reservoirs and short intervening open-river (free-flowing) reaches with highly altered hydrology between dams and reservoir pools (Galat and Lipkin, 2000). Below each dam, the river has substantially reduced peak flood magnitudes, shifted seasonality of high and low discharge events, and overall reduced intraannual discharge variability (Hesse and Sheets, 1993; Galat and Lipkin, 2000) (fig. 13). Additionally, the magnitude, duration, and daily variability of low discharges in the middle and lower Missouri River have increased (Galat and Lipkin, 2000; Ehlman and Criss, 2006). The magnitudes of the hydrologic alterations from dams on the middle Missouri River are attenuated downstream from the lowermost dam, Gavins Point, because of contributions from less regulated tributaries and are not detectable in the reaches of the middle and lower Mississippi River (Jacobson and Galat, 2008; Harmar and Clifford, 2006).

B. In the upper Mississippi and Ohio Rivers, the system of locks and dams raises the stage of low-magnitude discharges (the goal of the structures) to allow for reliable and safe navigation, but the stages of higher discharges are reduced or unchanged because the dams are overtopped or operated as a run-of-river during high-magnitude discharges (Chen and Simons, 1986). Loss of storage because of sedimentation in the pooled reaches behind the dams has steadily increased the flood stage at older dams since construction such that it is nearly equal to predam levels and, subsequently, the number of flood days in reaches upstream from the navigation pools also has steadily increased over time (Grugbaugh and Anderson, 1989).

C. Changes to hydrology in the MRB also have been associated with the construction of dikes, revetments, and levees (Belt, 1975; Criss and Shock, 2001). Wing dikes have concentrated flow into narrower channels and, in combination with reduced overall sediment supplies, caused bed incision, resulting in progressively lower stages over time for lower magnitude discharges (fig. 14). However, wing dikes, in combination with levees, have reduced overall channel capacity for intermediate and higher discharges, increasing stages over time (Pinter and Heine, 2005). Levee construction is still active within the MRB, and the restriction of overbank discharges by levees has increased flood stages by up to 4 m in various locations over the past 50 years (Belt, 1975; Criss and Schock, 2001; Pinter and Heine, 2005). In the lower Mississippi River, the increase in flood stages over the past 50 years has been offset by the USACE cutoff program, which caused an initial reduction of stages by as much as 4.8 m. However, as much as 40 percent of the stage reduction from the cutoff program has been regained at Vicksburg, Mississippi, indicating that flood stages over time may return to precutoff elevations in the absence of additional engineering (Criss and Shock, 2001; Harmar and others, 2005).

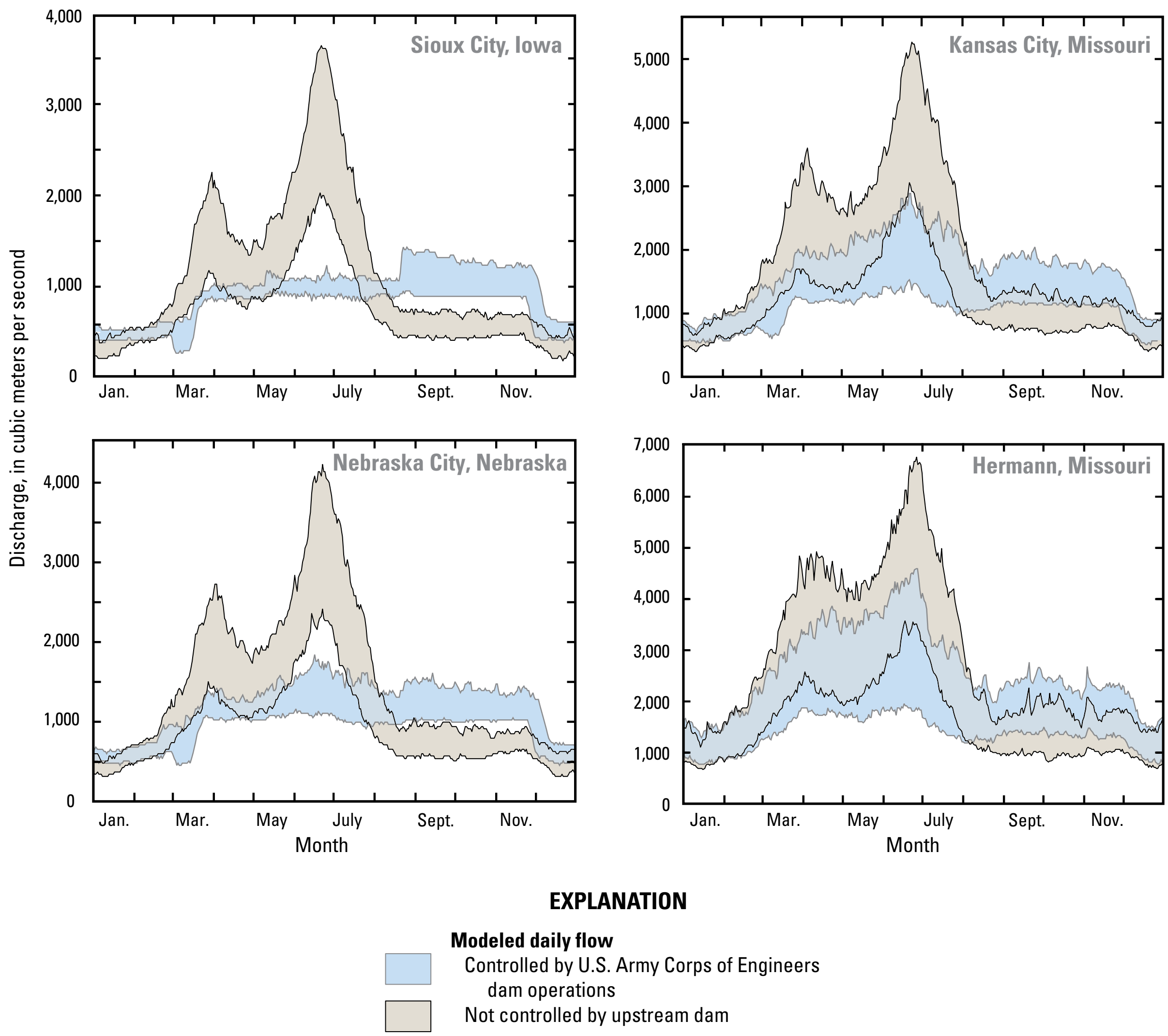


Figure 13. Discharge duration of the 25-percent to 75-percent exceedance boundaries for four locations on the Missouri River downstream from Gavins Point Dam (modified from Jacobson and others, 2009).

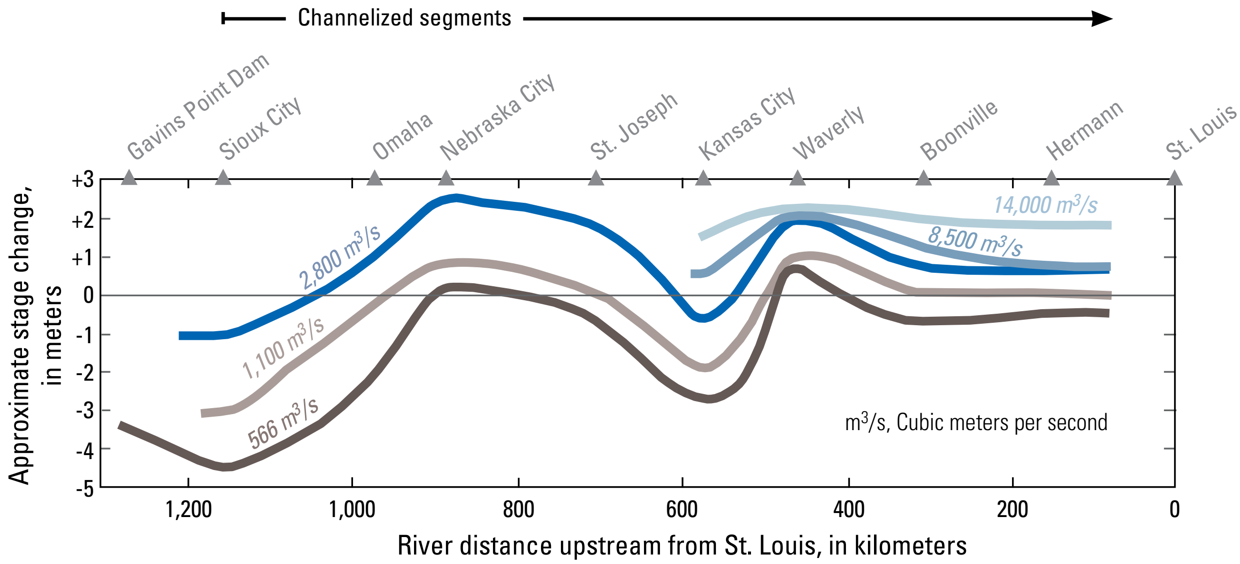


Figure 14. Generalized longitudinal patterns of bed-elevation changes along the lower Missouri River from 1954 to the mid-1990s depicted as stage changes for constant discharge at measurement stations downstream from Gavins Point Dam (modified from Jacobson and Galat, 2008).

Effects on Sediment Transport

A. Prior to major river engineering, the combined Mississippi-Atchafalaya River system is estimated to have transported an annual average of approximately 400 million metric tons of sediment to coastal Louisiana (Meade and Parker, 1985; Kesel and others, 1992). From 1987 to 2006, annual sediment delivery to the coastline averaged approximately 170 million metric tons (fig. 15), a 60-percent decrease from predevelopment estimates (Rebich and Demcheck, 2007; Meade and Moody, 2010). Much of the decrease in sediment loads has been attributed to the construction of the systems of dams along the Missouri and Arkansas Rivers (Meade and Parker, 1985). After completion of the six main-stem dams on the middle Missouri River, suspended-sediment concentrations on the lower Missouri River declined by as much as 80 percent; average annual sediment load (fig. 16) transported to the Mississippi River declined by at least 60 percent (Keown and others, 1986; Blevins, 2006). Similarly, construction of flood control and navigation dams on the Arkansas River resulted in a nearly 90-percent decrease in sediment transported to the lower Mississippi River from approximately 93 million metric tons to 11 million metric tons (Keown and others, 1986).

B. Land accretion in wing-dike fields on the lower Missouri River has been estimated to account for as much as 14 percent of the decline in mean annual suspended-sediment loads of the Missouri River Basin between 1910 and 1981 (Jacobson and others, 2009). Similar accounts of land accretion around wing dikes have been reported in the lower Mississippi River (Kesel, 2003), indicating that sediment accumulating in dike fields, during and for periods after dike construction, may account for a substantial part of initially estimated declines in basinwide sediment loads (fig. 17). However, because dike fields have already accreted substantial volumes of sediment, their efficacy as sediment traps today is negligible. Construction of wing dikes also coincided with channel straightening and, on the lower Mississippi River, channel cutoff programs, which required substantial bank protection to ensure sustained channel stability. The emplacement of revetments further reduced sediment supplies by causing a 90-percent decline in bank caving, a substantial source of the total sediment load in the lower Mississippi River prior to major channel engineering projects (Kesel and others, 1992).

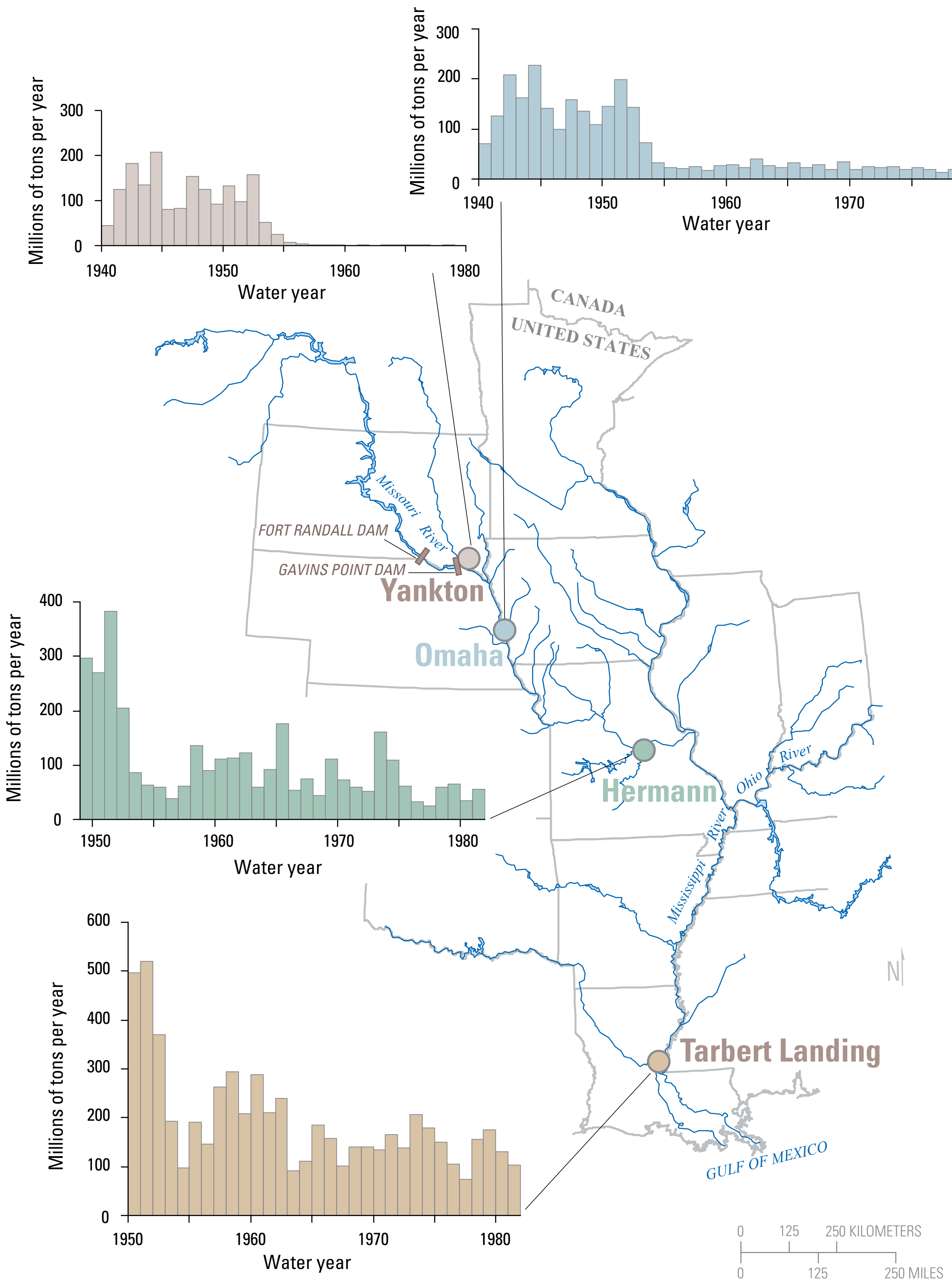


Figure 15. Total suspended-sediment discharge at stations along the lower Missouri and lower Mississippi Rivers (modified from Meade and Moody, 2010).

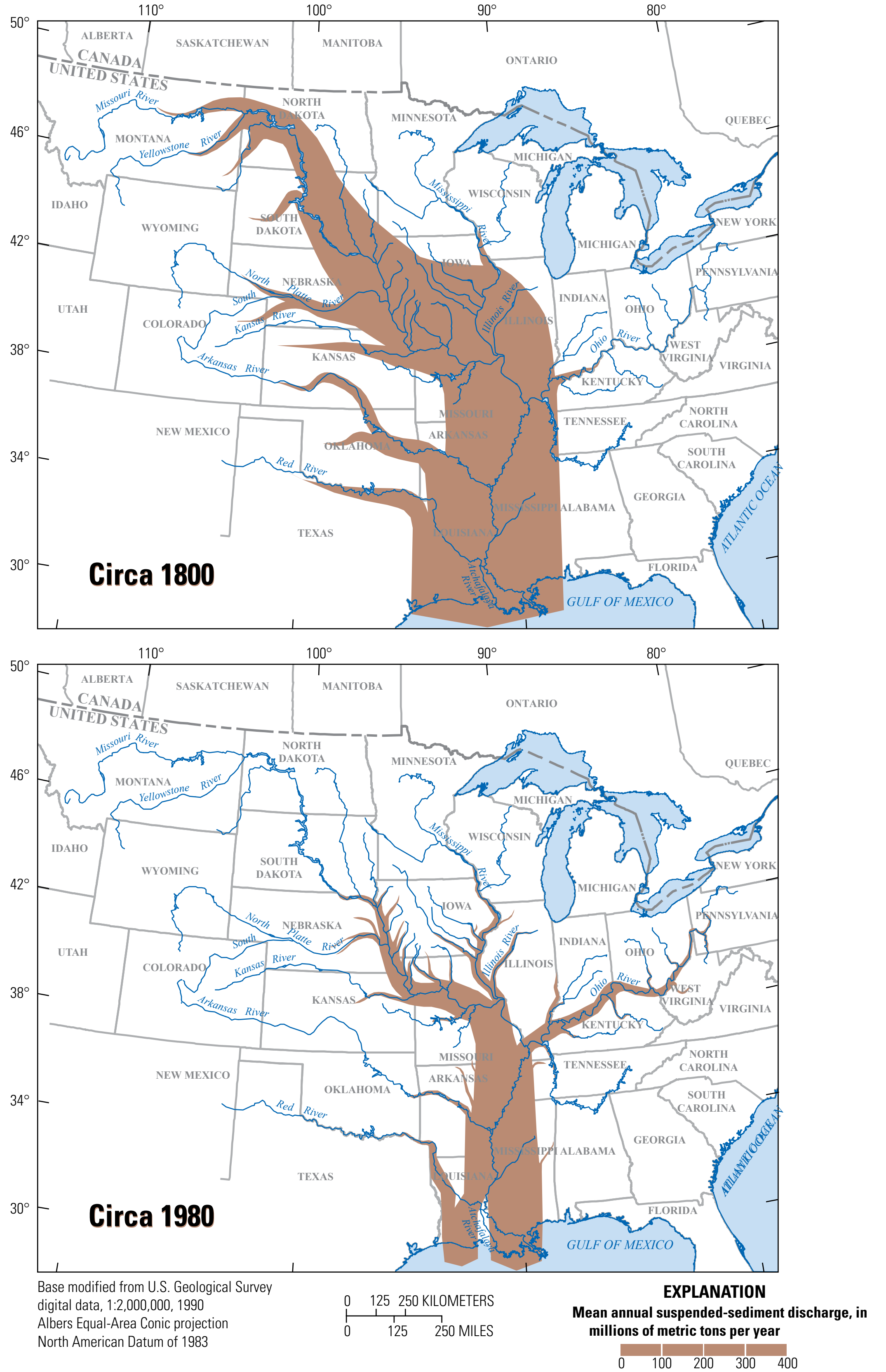


Figure 16. Estimated predevelopment (circa 1800) and postdevelopment (circa 1980) mean annual suspended-sediment discharge along the Mississippi River and major tributaries (modified from Meade and Moody, 2010).

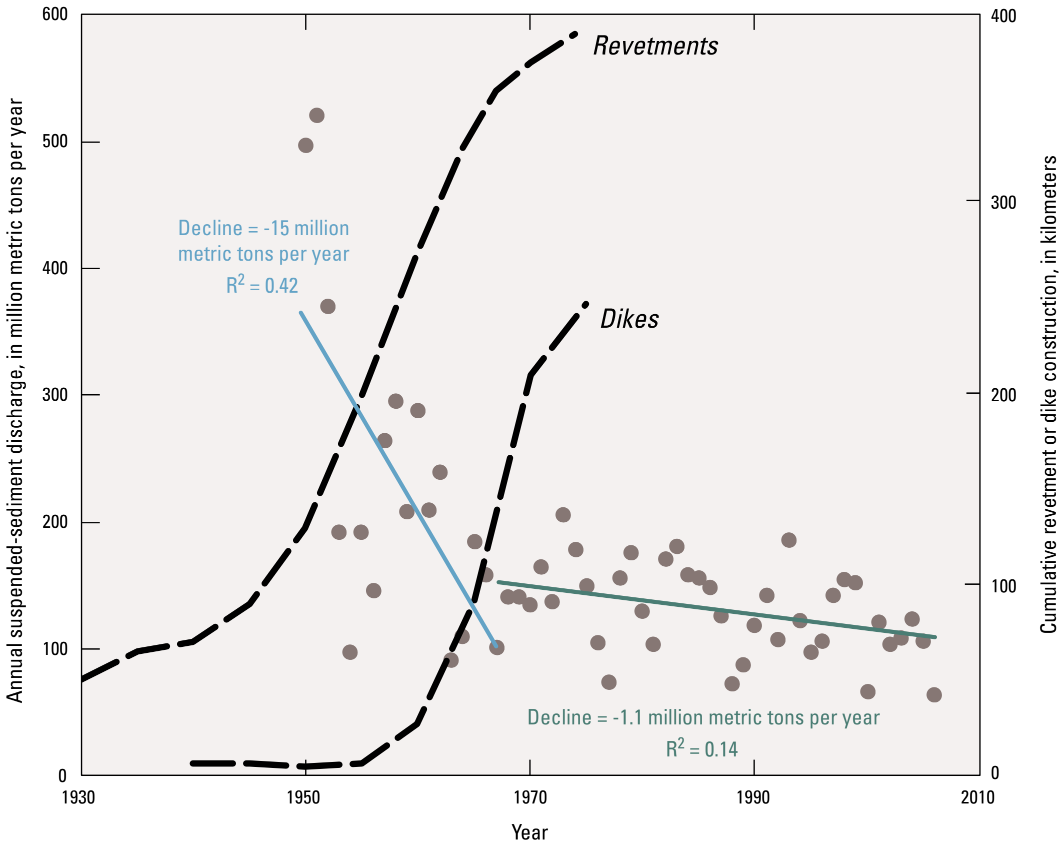


Figure 17. Time series of annual suspended-sediment discharge of the Mississippi River at Tarbert Landing, Mississippi, and the rate of construction of engineered dikes and bank revetments along the lower Mississippi River (Meade and Moody, 2010).

C. Since the more pronounced changes associated with the completion of major channel-engineering projects, sediment transport has continued to gradually decline (Meade and Moody, 2010). Continued declines in sediment transport have been attributed to improvements in agricultural conservation practices and material extraction (dredging). These processes are more temporally and spatially diffuse than closure of large main-stem dams and were occurring simultaneously with dam and wing-dike construction, making estimates of the magnitude of effects difficult (Meade and Moody, 2010) (fig. 17). For example, although widespread deforestation and poor tillage practices substantially increased sediment yields from agricultural lands of the upper MRB in the late 19th and early to mid-20th centuries, much of the additional sediment was stored in tributary bottomlands and flood plains, resulting in a small net change to total sediment delivered to the Mississippi River main stem (Trimble, 1999; Knox, 2006). Commercial dredging also has been identified as contributing to reductions in sediment supply. Dredging operations generally are concentrated around metropolitan areas and have been estimated to extract an average of 5 to 7 million metric tons of sediment per year in the upper Mississippi and lower Missouri Rivers. In the lower Missouri River, 7 million metric tons of sand are the equivalent of 40 percent of the sand fraction of the most recent estimate of the average annual suspended-sediment load (Jacobson and others, 2009).

Effects on River Geomorphology

A. The geomorphology of the MRB has been affected by dams, dikes, revetments, and levees in three primary ways: (1) channel simplification and reduced dynamism, (2) lowering of channel-bed elevation, and (3) disconnection of the river channel from the flood plain.

B. Prior to major human modification, main-stem channels of the MRB in many locations were more complex and dynamic, exhibiting substantial planform alignment shifts from year to year, which resulted in a physically and biologically diverse channel and flood-plain structure (Yin and Nelson, 1996; Moody and others, 2003; Harmar and Clifford, 2006). This was particularly true of the lower Missouri and upper Mississippi Rivers, where the river channels were composed of series of sandbar complexes, side channels, and backwaters, and incorporated substantial amounts of large woody debris (Hesse, 1987). Channel simplification has been accomplished through a combination of river-channel shortening (reduction in curvature) and consolidation of multiple channel threads to a single channel (fig. 18) (Yin and Nelson, 1996). River-channel lengths in the lower Missouri River decreased by approximately 120 km, or 10 percent, over the past 200 years because of natural and engineered cutoffs; active channel area has decreased by 41 percent, and the number of islands and sandbars has decreased by 99 percent (Funk and Robinson, 1974; Hallberg and others, 1979). In the upper and middle Mississippi River, overall channel position and length have not changed substantially, and island areas have increased in pools behind locks, but open-channel reaches have simpler geometry and reduced dynamism because of side-channels cutoffs, wing-dike construction, and emplacement of revetments (Chen and Simons, 1986; Grugbaugh and Anderson, 1988). The channel cutoff program in the lower Mississippi River initially resulted in a total engineered shortening of 331 km. However, the tendency of the river to regain curvature, resulted in a net shortening of 235 km, and the emplacement of revetments has kept the channel approximately the same length and in the same position since the 1970s (Winkley, 1977; Biedenharn and others, 2000). Although the channel of the lower Mississippi is much shorter than prior to the cutoff program, the channel is, on average, wider than prior to the cutoff program (Kesel, 2003).

C. Riverbed elevation in the MRB has lowered (scoured) in most locations where measurements are available. Streambed lowering in the lower Missouri River has resulted from a reduction in sediment supply, flow concentration by wing dikes, and localized material extraction (dredging) (fig. 19) (Jacobson and others, 2009). Between Gavins Point Dam and Sioux City, Iowa, the riverbed has scoured as much as 4 m because the river no longer receives sediment from upstream but still retains a large sediment-transport capacity (Schmidt and Wilcock, 2008). Downstream from Sioux City, Iowa, the Missouri River channel is substantially engineered, and has scoured between 2 and 5 m because of a combination of reduced sediment supply, constriction of the channel by wing dikes, and channel dredging (National Research Council, 2011). Riverbed elevation in the upper and middle Mississippi River has been locally scoured and aggraded. Scour generally has been associated with reaches below dams and with channel dredging, although reaches of the upper and middle Mississippi River do not exhibit a consistent pattern or trend of aggradation or degradation over time. River stage per unit discharge lowered between 0.5 and 5 m in the lower Mississippi River in response to channel shortening associated with the USACE cutoff program (Kesel, 2003). River-stage lowering in the lower Mississippi River has been interpreted to be the result of a combination of scour, which is apparent between at least Memphis, Tenn., and Natchez, Miss., and increased channel slope resulting in higher overall stream power (Smith and Winkley, 1996; Kesel, 2003).

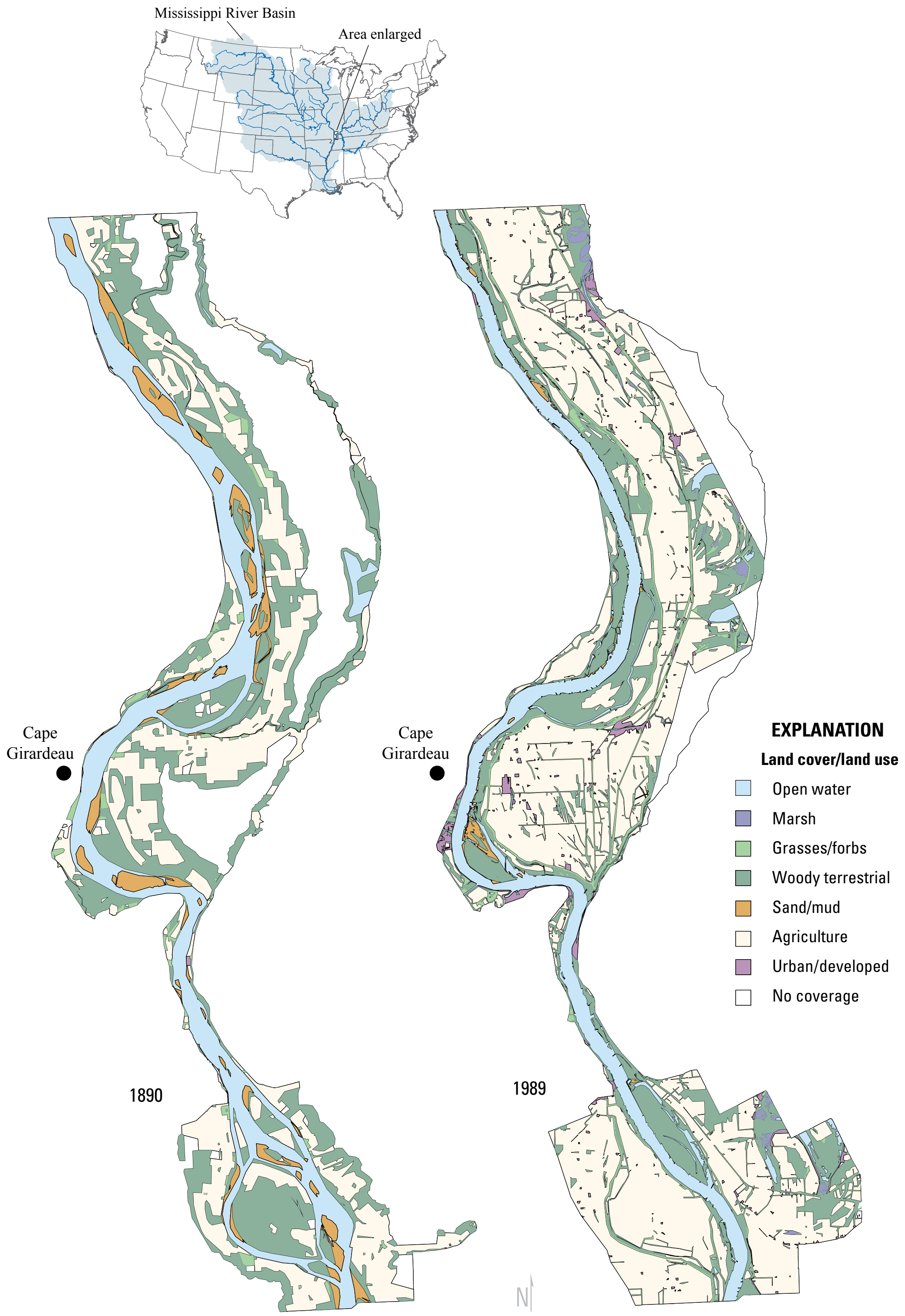


Figure 18. Changes in channel and flood-plain configuration from 1890 to 1989 along the lower Mississippi River (modified from Mac and others, 1998).

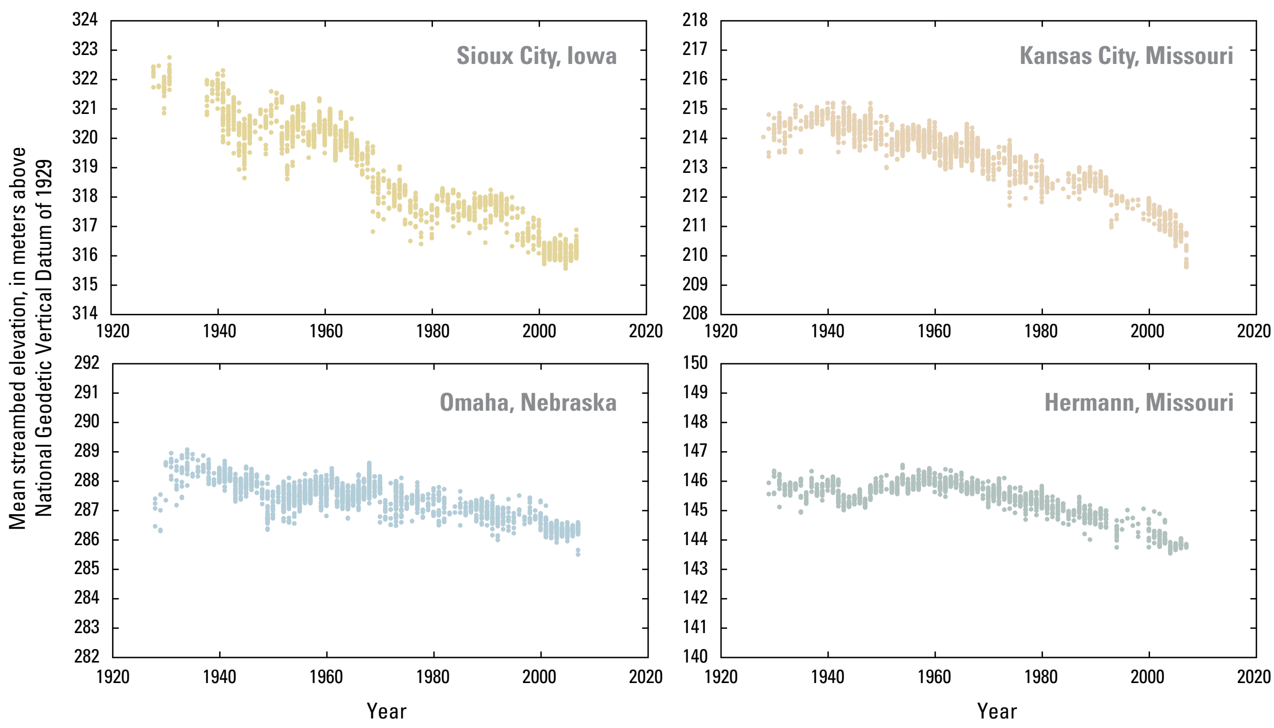


Figure 19. Temporal trends in river-bed elevations for 50- to 90-percent exceedance discharges at four streamflow-gaging stations along the lower Missouri River (modified from Jacobson and others, 2009).

D. Prior to major engineering projects, the Mississippi River and its tributaries flooded low-lying lands of the flood plain adjacent to the river semiannually and the entire valley bottom during extreme events (Yin and Nelson, 1996). Cyclical flooding was a fundamental ecosystem process that was essential to deliver nutrients to the flood plain, replenish off-channel wetlands, and regenerate aging riparian forest galleries (Galat and others, 1998; Dixon and others, 2010). The construction of levees, lowering of the riverbed elevation, and, in some locations, the reduction of peak-discharge magnitudes has resulted in a nearly universal disconnection of the river main channel from the flood plain, except during extreme flood events (Pitlick, 1997; Galat and others, 1998). In the lower Missouri River, the reduction in annual peak-discharge magnitudes because of flood-control dams, the lowering of the riverbed elevation from reductions in sediment supply and wing-dike construction, and the construction of a massive system of levees has resulted in a 90-percent reduction in flood-plain inundation (Hesse and others, 1989). In the upper Mississippi River, flood-plain inundation in open river reaches has been substantially reduced because of riverbed scour and levee construction; in pooled reaches, historical flood plains are permanently inundated or have converted to wetlands/marshes because of sedimentation and increased groundwater levels (fig. 20) (Yin and Nelson, 1996). In the lower Mississippi River, the increase in channel capacity associated with the USACE channel cutoff program, in combination with 3,000 km of levees, has reduced flood-plain inundation by approximately 90 percent relative to the preengineered condition (Kesel, 2003).

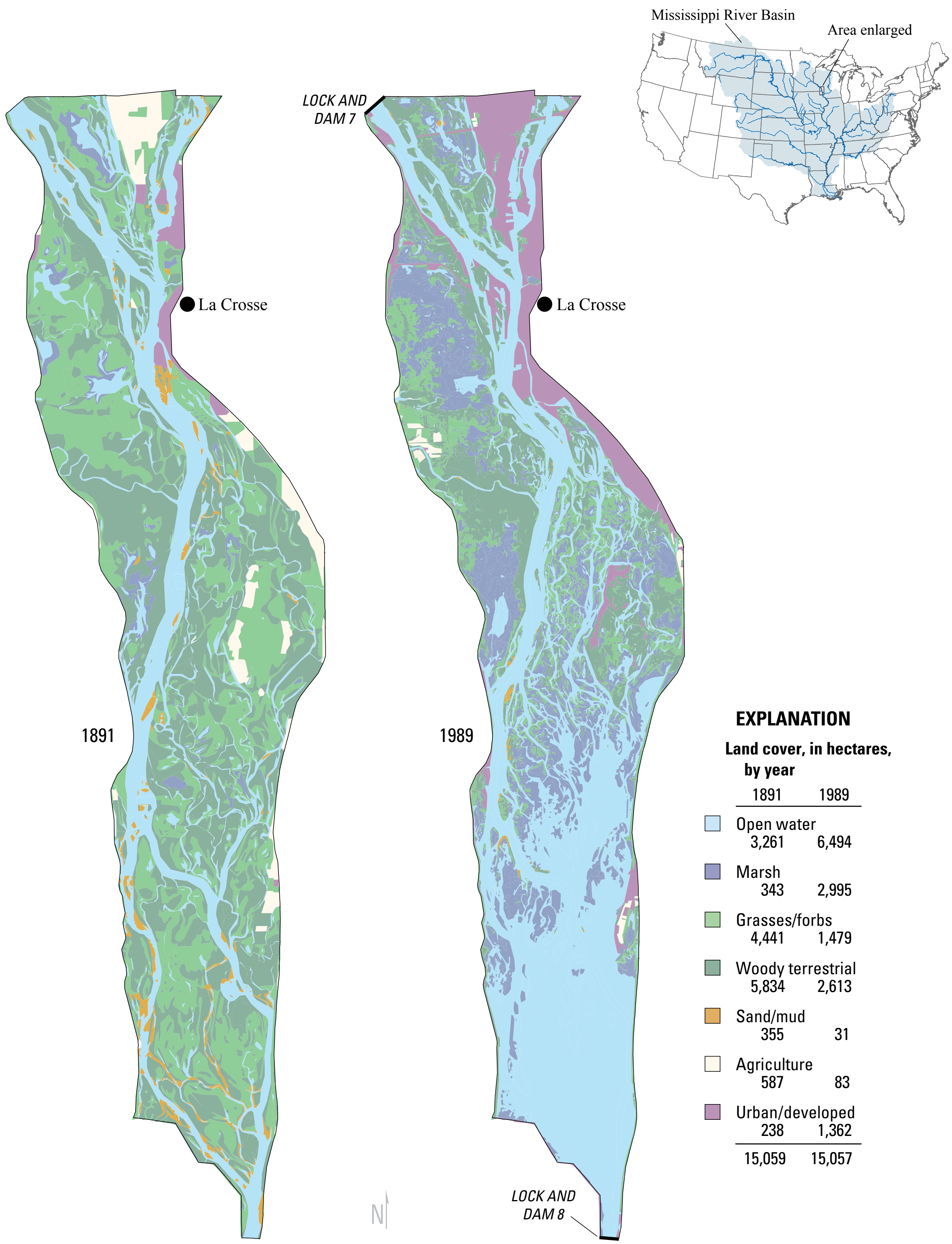


Figure 20. Changes in land cover from 1891 to 1989 along the reach of the upper Mississippi upstream from lock and dam 8, near LaCrosse, Wisconsin. The dam for pool 8 was completed in 1938 (modified from Mac and others, 1998).

Effects on Water Quality and Fish Communities

Damming a free-flowing river to create an impoundment (reservoir) changes the river upstream and downstream from the dam. As it regulates discharge, the dam changes the magnitude, duration, and timing of discharge downstream, and it changes the physical and chemical condition of water as well as ecological conditions both upstream and downstream. Dams result in upstream-downstream shifts in biotic and abiotic patterns and processes (Ward and Stanford, 1995); the direction and extent of the shift depend on the variable of interest and are a function of the position of the dam along the river continuum (Vannote and others, 1980). Reregulation of discharges from dams typically results in alternating series of lentic (still water, lakes) and lotic (flowing water) ecological functioning reaches (Ward and Stanford, 1983), affecting physical (temperature), chemical (nutrients—nitrogen and phosphorus, organic matter, metals, and others), and biological characteristics at the population, community, and ecosystem levels. Regulated rivers regain more natural attributes as distance downstream from the dam increases in relation to the mode of dam operation (Stanford and others, 1996). The extent of these changes downstream from the dam (the tailwater) is a function of the size of the impoundment, changes to hydrology, downstream channel geomorphology, and number, size, and nature of tributary inflows and riparian conditions (Ashby and others, 1997).

Some of the most dramatic effects of dams result from the change of the downstream flood regime (Baxter, 1977). One purpose of building dams is to reduce annual variations in water level, making the terrestrial flood plain habitable throughout the year and allowing its ecosystem to become more mature as a terrestrial ecosystem. Often, this altered terrestrial flood plain will be replaced by a different ecosystem maintained in a state of immaturity by the practice of agriculture. In a natural system, floods deliver nutrient-rich sediments to the flood-plain floor and the river delta, acting as a natural fertilizer to the flood-plain soils. Dams trap sediments and reduce peak flood discharges, keeping water flows within the channel banks (as designed). This modification to the river continuum prevents nutrient-rich sediments from replenishing the flood plain or delta plain. Consequently, if a river runs into an ocean, the nutrients that would have otherwise been deposited (filtered out) on the flood plain, now discharge into the estuaries and coastal sea waters. Consequently, deltaic land converted to agriculture must be supplemented with inorganic commercial fertilizers because of a lack of natural nutrient delivery. Excess fertilizer runoff then becomes available for transport downstream, enriching the downstream ecosystems.

Effects on Water Quality

A. The freshwater discharge of the Mississippi River and its associated sediment and nutrient loads have strongly influenced the physical and biological processes in the northern Gulf of Mexico over geologic time and past centuries, and even more strongly during the last half of the 20th century (National Research Council, 2008). The Mississippi River is the dominant source of freshwater, sediment, and nutrients to the northern Gulf of Mexico (National Research Council, 2008), carrying roughly 96 percent of annual freshwater discharge, 98 percent of total nitrogen, and 98 percent of total phosphorus load (Dunn, 1996; Rabalais and others, 2002). Sediments carry nutrients and other contaminants. As a result of dam construction on the Missouri River, the amount of sediments transported down the Mississippi River during the 1700s and 1800s has been reduced (Meade, 1995). Now the sediment inputs from the upper Mississippi and Ohio Rivers are proportionally greater, and these rivers carry the largest proportions of the total load of nutrients in the form of nitrate (fig. 21).

B. The National Research Council (2008) reported that about 90 percent of the nitrogen load reaching the Gulf of Mexico from the Mississippi River is from nonpoint sources, including about 60 percent from fertilizer and mineralized soil nitrogen (Goolsby and others, 1999). The remaining 10 percent is from a mix of sources that include municipal and industrial point sources. Loadings of total phosphorus are relatively high and about equally divided among the combined upper and middle Mississippi, lower Mississippi, Ohio, and Missouri River Basins. Alexander and others (2008) determined that corn and soybean cultivation is the largest contributor of nitrogen (52 percent), followed by atmospheric deposition (16 percent), whereas phosphorus originates primarily from animal manure on pasture and rangelands (37 percent) followed by lands where corn and soybeans are grown (25 percent). The proximity of sources to streams and rivers is an important determinant of nitrogen and phosphorus delivery to the northern Gulf of Mexico (fig. 22) and the proportion of in-stream nitrogen and phosphorus delivered to the Gulf of Mexico increases with stream size; once in the river, it typically stays in the water. Reservoir trapping of phosphorus causes large local- and regional-scale differences in phosphorus delivery (Alexander and others, 2008).

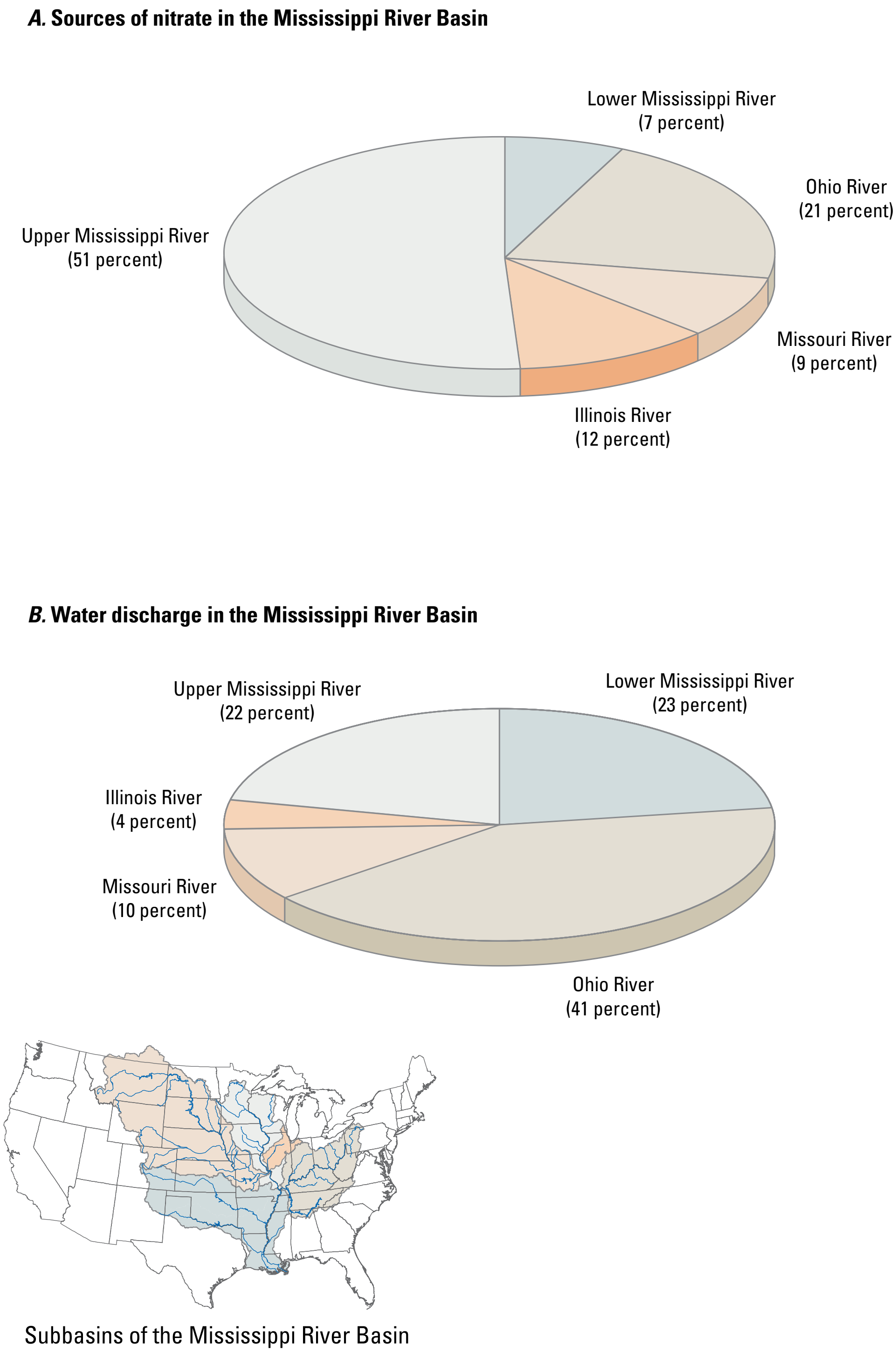


Figure 21. Proportion of nitrates and water discharge from tributaries in the Mississippi River Basin (modified from Meade, 1995).

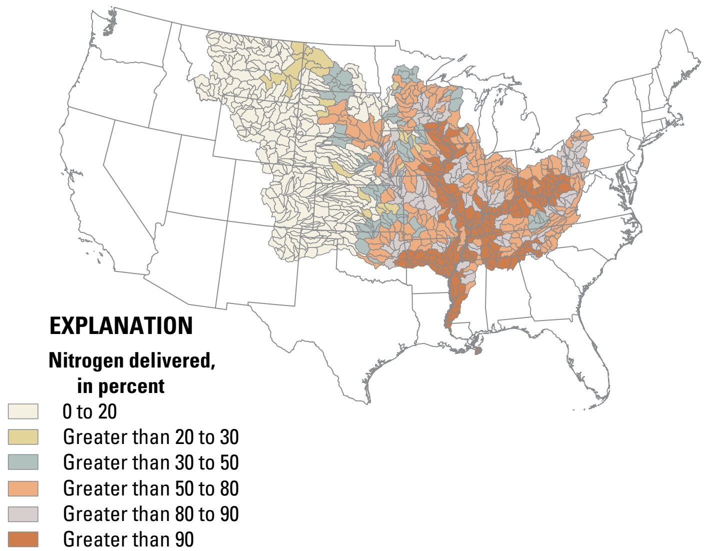


Figure 22. Percentage of nitrogen export from approximately equally sized interior watersheds of the Mississippi River Basin delivered to the Gulf of Mexico (modified from Alexander and others, 2000).

C. Increased nutrient enrichment in the northern Gulf of Mexico resulting from increased nutrient loading from the Mississippi River has resulted in the degradation of water quality as more algae grow, which increases turbidity and depletes oxygen (hypoxia) in the lower depths that typically affect 10 to 50 percent of the water column, and may reach within 2 m of the surface (Rabalais and others, 2002). The area affected by hypoxic conditions is commonly known as the “dead zone” because few marine animals can survive in the low oxygen concentrations (Rabalais and Turner, 2001). Swimming fish, crabs, and shrimp must escape or succumb to the low oxygen concentrations; other, less mobile organisms eventually suffocate and die. Additional factors that contribute to the hypoxia in the northern Gulf of Mexico include the inflow of poorly oxygenated waters from the deep gulf, river loading of organic carbon, channelizing and coastal wetland loss, nitrogen flux from the atmosphere or deep gulf waters, and climate-induced alterations in water flux from the MRB (Rabalais and others, 2002). The size of the hypoxic zone south of the Mississippi River in the Gulf of Mexico averaged 12,900 km^2 between 1985 and 2002 (Rabalais and Turner, 2006) (fig. 23) and was greatest in 2002 with 22,000 km^2. The extent of the oxygen-depleted waters was as large as the States of New Jersey or Rhode Island combined with Connecticut, and at its largest was the size of Massachusetts (National Research Council, 2008).

Effects on Fish Communities

A. Changes in the discharge regime from engineered structures can have direct and indirect effects on fish communities. The Mississippi River supports a rich fish community as discharge increases from its headwaters in the north, a cool temperate climate, flowing south more than 3,500 km to its subtropical outlet in the Gulf of Mexico (Schramm, 2004). The 195 species of freshwater fish in the main stem of the Mississippi and Atchafalaya Rivers represent almost one-third of the freshwater fish species in North America (Fremling and others, 1989). Most fish require several different habitats to complete a life cycle, and the quantity and quality of habitats have diminished in many reaches (Wiener and others, 1998) influenced by natural and human barriers to migration. The upper Mississippi River provides many aquatic habitats, including main channel, tail water, main-channel border, side channel, navigation pool, flood-plain lake or pond, slough, and tributary mouth (Littlejohn and others, 1985; Fremling and others, 1989; Wiener and others, 1998). These habitats can differ markedly in current velocity, depth, temperature, water quality, bottom substrate, vegetative structure, food resources, and other characteristics. The navigation pools in the upper Mississippi River are aging, and overwintering habitats for fish have declined as sedimentation reduces water depth (McHenry and others, 1984; Bhowmik and Adams, 1989; Holland-Bartels, 1992; and Gent and others, 1995). Some fish

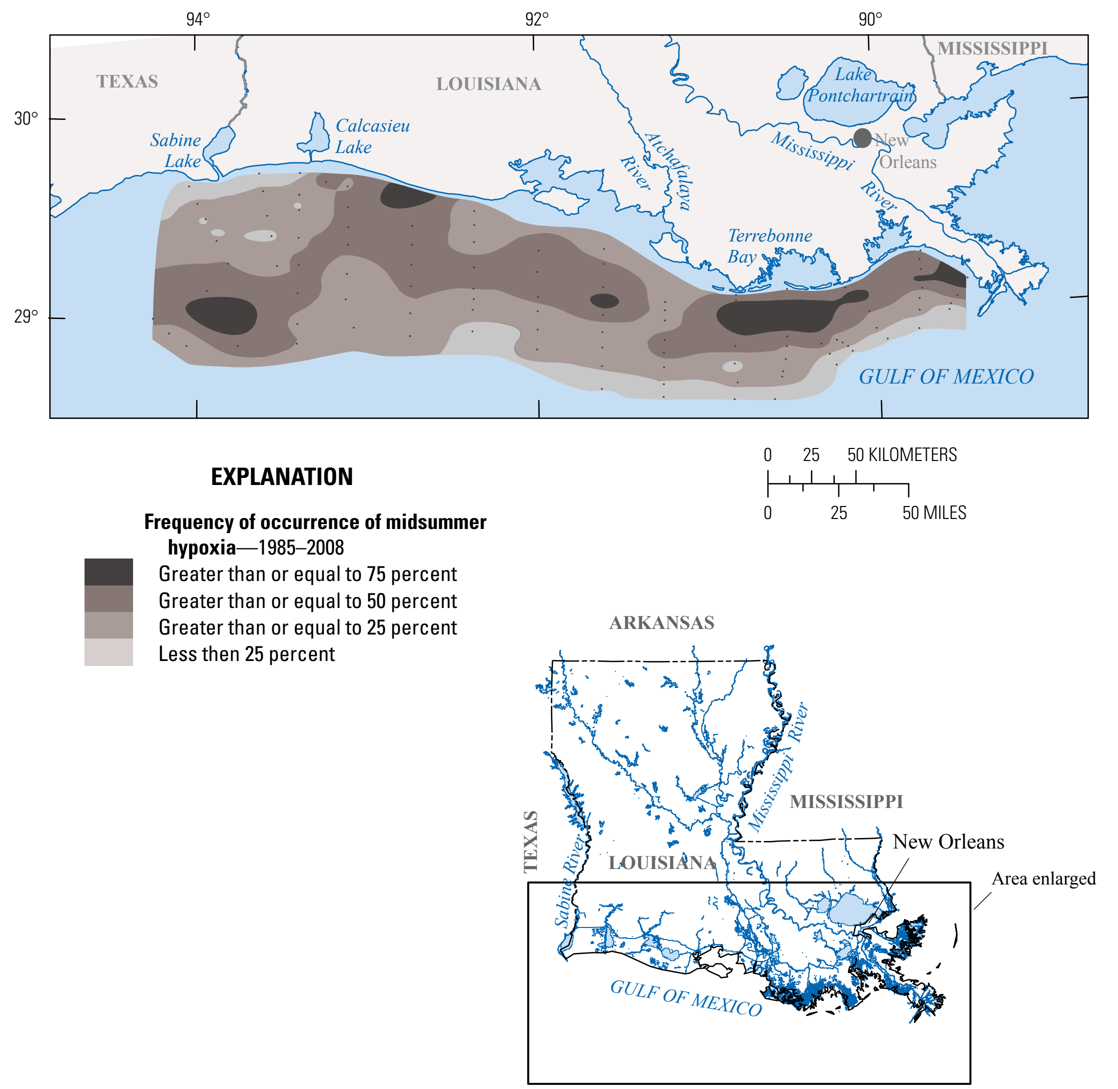


Figure 23. Frequency of occurrence of midsummer hypoxia in the Gulf of Mexico, 1985–2008 (modified from a figure provided courtesy of Nancy Rabalais, Louisiana Universities Marine Consortium).

that inhabit swift-current habitats have declined in the upper Mississippi River since the construction of navigation dams (Wiener and others, 1998). Reproduction of paddlefish in the upper Mississippi River may be adversely affected by dams, which could impede paddlefish access to suitable spawning habitat.

B. In the main stem of the lower Mississippi River, swift-current habitats include the river channel, natural steep banks, revetted banks (covered with protective materials, mostly limestone rock to prevent erosion), and flowing sandbars (Wiener and others, 1998; Baker and others, 1991). Dike fields in the lower Mississippi River often contain many fish species (Pennington and others, 1983). Fish that inhabit swift-current habitats in the unimpounded lower Mississippi River have not declined as much as in the upper Mississippi River (Pflieger, 1975; Baker and others, 1991) with the exception of the pallid sturgeon. The decline of the pallid sturgeon, a native species which is listed as endangered by the U.S. Fish and Wildlife Service, may be attributable to channelization of the open river below St. Louis, Mo. (Wiener and others, 1998).

C. The Missouri River also supports a rich fish community from its headwaters in Montana flowing more than 3,700 km to its confluence with the Mississippi River near St. Louis (Galat and others, 2005). Seventy-three of the 136 Missouri River species are classified as “big river” species. Populations of 17 species are increasing and 9 of these are introduced species. Populations of 24 species are declining, and all but one of these are native species. The history of changes in the fish communities up and down the Missouri River has resulted from the complex interactions between natural and human factors. However, the richness of the Missouri River’s native fish populations remains relatively intact despite these assaults; no native fish have yet been extirpated (Galat and others, 2005), although the pallid sturgeon is on the Federal list of endangered species. Nevertheless, the widespread and long history of human intervention has contributed to declines of about 25 percent of the species. Partly as a result of these declines, the National Research Council (2002) has suggested that the degradation of the Missouri River ecosystem will continue unless the part of the hydrologic and geomorphic processes that sustained the preregulation Missouri River and flood-plain ecosystem is restored. Otherwise, the Missouri River ecosystem will face the prospect of extinction of species. These processes include flood pulses that emulate the natural hydrograph and cut-and-fill alluviation associated with river meandering.

Effects on the Mississippi River Delta

A. The Mississippi River delta and associated coastal wetlands are built from six delta complexes (1) Maringouin-Sale-Cypremort, (2) Teche, (3) St. Bernard, (4) Lafourche, (5) Plaquemines-Balize, and (6) Atchafalaya-Wax Lake (fig. 24) (Blum and Roberts, 2009), which are the products of 6,000 to 8,000 years of cyclical depositional and erosional processes known as the “delta cycle” (Roberts, 1997; Coleman and others, 1998). The delta cycle consists of two primary phases: (1) a river-dominated phase in which the complex is protruding and expanding onto the sea floor, and (2) a marine-dominated phase in which the delta complex is progressively abandoned by the river, the delta subsides, and the perimeter of the delta is gradually reworked and eroded by wave action. Two delta complexes are currently active on the Mississippi River Delta Plain: the Plaquemines-Balize (also known as the “Birdfoot”) and the Atchafalaya-Wax Lake. The Plaquemines-Balize delta complex is currently river-dominated but is slowly transitioning to a marine-dominated phase. The Atchafalaya distributary channel, which has been capturing discharge from the Mississippi River since at least 1500, began building a delta in the early to middle 20th century; the Wax Lake lobe

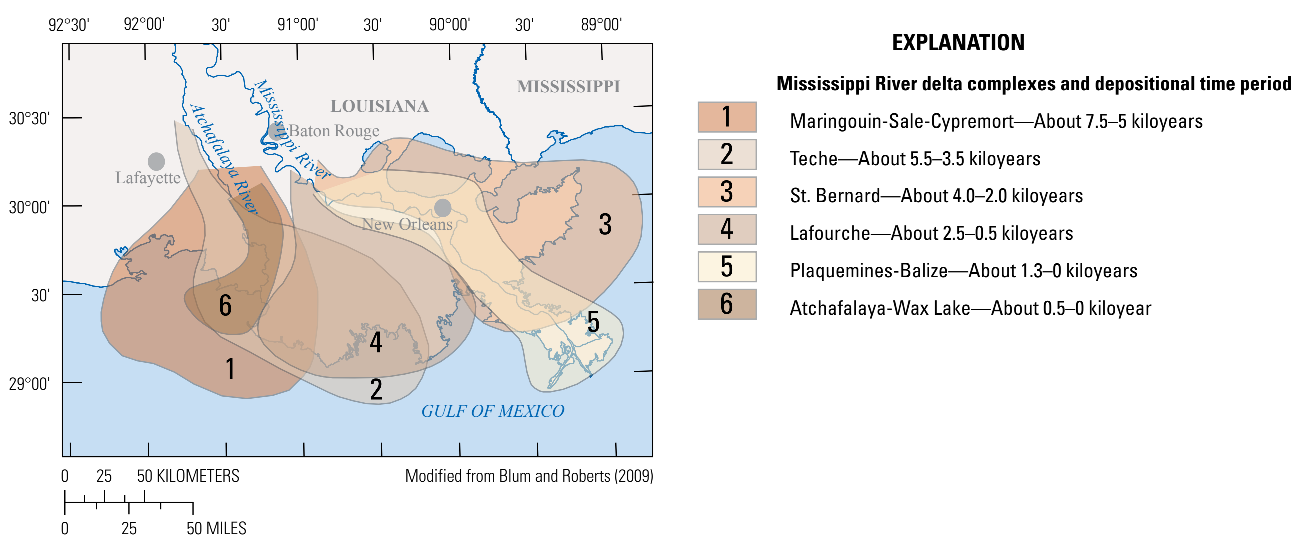


Figure 24. Generalized extent and depositional time periods of the Mississippi River Delta complexes.

(not shown on fig. 24) of the Atchafalaya-Wax Lake delta complex began building in the middle of the 20th century with the construction of a diversion canal off of the Atchafalaya distributary. The slow capture of flow and sediment from the Mississippi River by the Atchafalaya distributary channel was stabilized in 1963 with the construction of the Old River Control Structure, and is currently limited to passing no more than 30 percent of the total discharge of the Mississippi River (Mossa, 1996).

B. Louisiana coastal wetlands support the largest commercial fishery in the 48 conterminous States (Couvillion and others, 2011). Since the early 20th century, approximately 4,900 km^2 of coastal lands, mainly wetlands, have been lost in Louisiana (Day and others, 2007a). Wetland losses are mainly associated with conversion to open water, but small fractions also are from wetland draining and associated vegetative community succession (Britsch and Dunbar, 1993). Land-loss rates accelerated from 17.4 km^2/yr in the early 20th century to approximately 40 km^2/yr by the late 1940s and were as great as 100 km^2/yr by the 1970s (fig. 25) (Britsch and Dunbar, 1993; Boesch and others, 1994). Since that time, rates have decreased to approximately 43 km^2/yr with intermittent greater rates of loss associated with recent hurricanes (Couvillion and others, 2011).

C. Causes for wetland and coastal land losses are a mix of natural and human-induced processes, which have interacted over varying spatial-temporal scales. The natural stability of the delta surface and associated wetlands is a complex balance between the relative rates of depositional processes that drive vertical and horizontal growth of the delta plain, and the processes of submergence and erosion, which drive loss of lands on the delta top and margins (fig. 26). Replenishment of wetland surface mass with sediment, as well as carbon fixing and sediment stabilization from vegetation growth, are the primary mechanisms by which the elevation of the delta surface remains stable against the counteracting forces of subsidence, sea-level rise, and storm surge (Paola and others, 2011). One of the primary

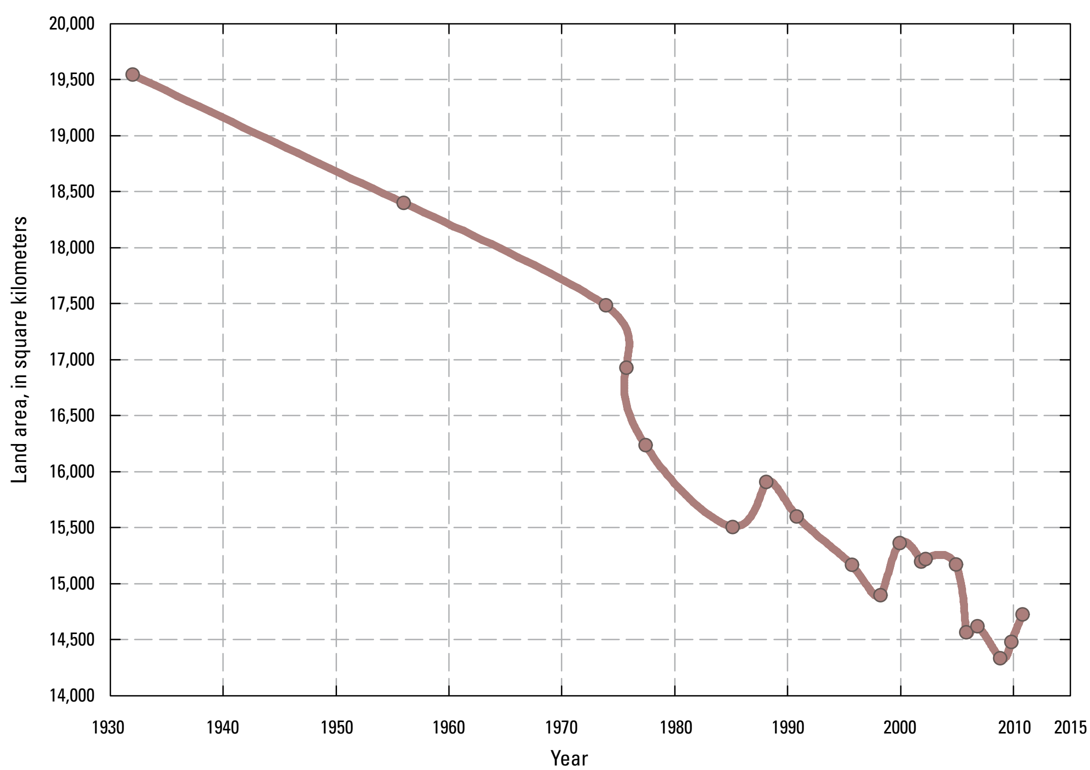


Figure 25. Time series of land-area changes in coastal wetlands of Louisiana, 1932 to 2010 (modified from Couvillion and others, 2011).

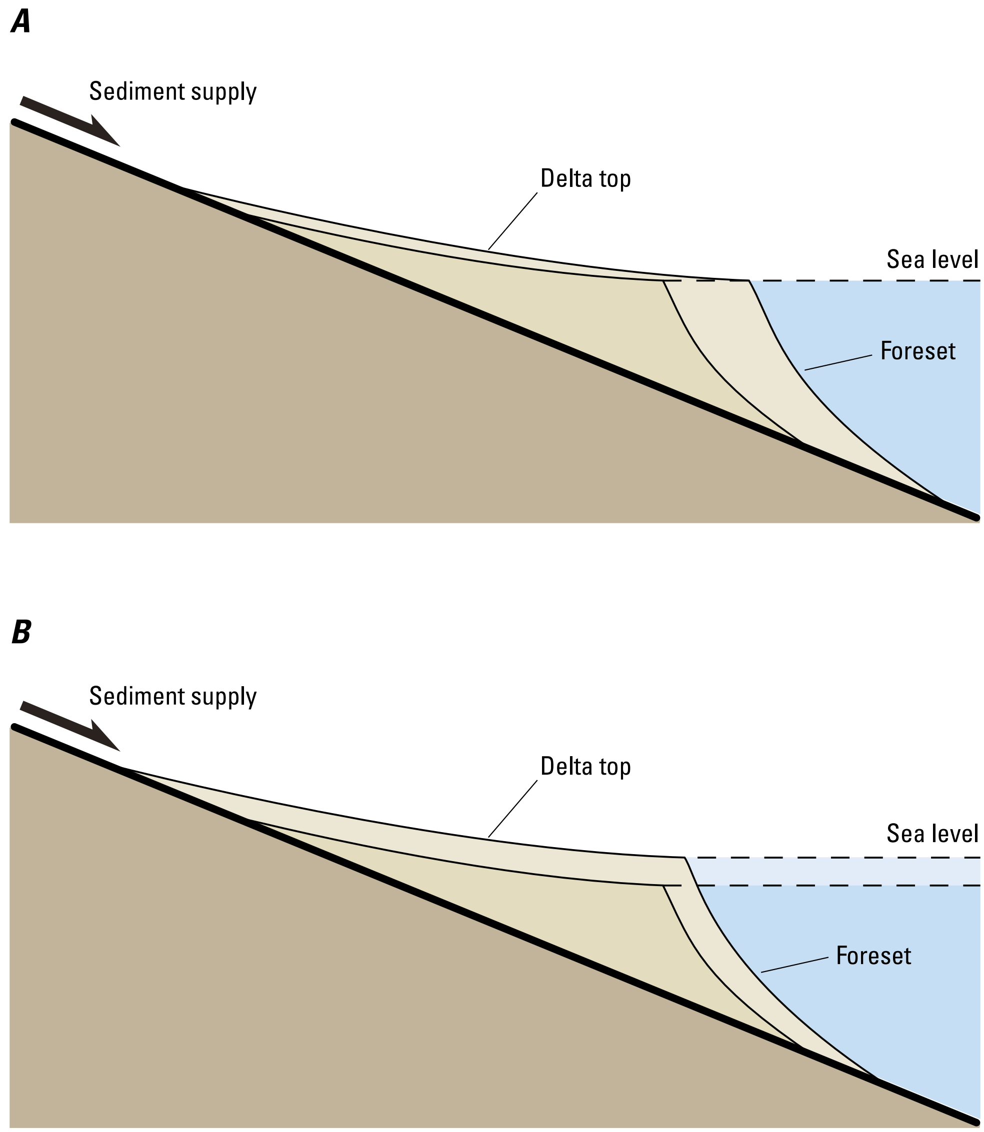


Figure 26. Cross sectional shape of a river delta depicting two mass balance scenarios. *A* quasistatic sea-level elevation. *B* rising sea level (modified from Paola and others, 2011; used, with permission, from the *Annual Review of Marine Science* volume 3 © 2011 by Annual Reviews www.annual reviews.org).

reasons for land loss in the Birdfoot complex of the Mississippi River Delta has been attributed to the construction of levees along distributary channels of the delta surface, which have compartmentalized and disconnected the delta surface from the channels. Sediments that would have otherwise been delivered to coastal basins when the river was overbank, and which nourish and replenish the adjacent wetlands, are now carried directly to the Gulf of Mexico (Paola and others, 2011). Additional losses of wetlands also are directly attributable to reduced sediment deliveries to the lower Mississippi River because of upstream reservoir construction, as well as several other factors including the removal of wetlands by canal dredging for navigation and the burying of wetlands with dredge spoil piles (Bass and Turner, 1997). Dredge-spoil piles also further contribute to compartmentalization of wetlands, similar to the effect of levees along delta distributaries. Saltwater intrusion, particularly along canals, and accelerated subsidence from petroleum fluid extraction also have been implicated as another potential cause of wetland deterioration and loss (Mallman and Zoback, 2007).

D. In response to the growing awareness of potential economic and ecological consequences of coastal wetland loss, the State of Louisiana began regulation of developmental activities affecting wetland loss in 1978. In 1990, the U.S. Congress enacted the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA), which has allocated between 30 and 80 million dollars annually and funded approximately 151 coastal restoration or protection projects in Louisiana. Since 1990, approximately 450 km^2 of coastal wetlands have been created and 2,200 km^2 have been protected by using CWPPRA funds (Coastal Wetlands Planning, Protection and Restoration Act, 2011).

E. Comprehensive coastal protection and restoration planning were undertaken by the State of Louisiana and the USACE after a devastating hurricane season in 2005. Current planning includes a "multiple lines of defense" strategy composed of a combination of coastal restoration alternatives, structural protection alternatives such as levees and floodwalls, as well as nonstructural protection alternatives such as landowner buyouts and raising existing structures (State of Louisiana, 2007; U.S. Army Corps of Engineers, 2009). Regardless of the success of these strategies, coastal land areas are, at best, projected to lose additional delta plain land area because, in the absence of increased sediment supplies from upstream, sediment deliveries may not be sufficient to fill the depositional space projected to be created by the combination of land subsidence and sea-level rise (fig. 27) (Blum and Roberts, 2009).

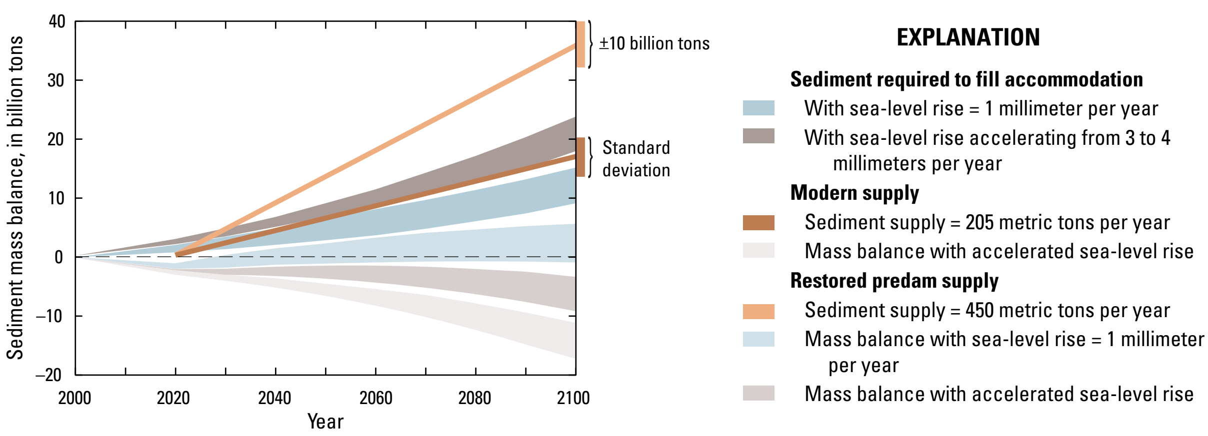


Figure 27. Time series of estimated sediment mass balance for the Mississippi delta region under varying scenarios of sediment supply, subsidence, and sea-level rise (modified from Blum and Roberts, 2009; used by permission from Macmillan Publishers Ltd.: Nature Geoscience copyright 2011).

Summary

The U.S. Geological Survey Forecast Mekong project is providing technical assistance and information to aid management decisions and build science capacity of institutions in the Mekong River Basin. A component of this effort is to produce a synthesis of the effects of dams and other engineering structures on large-river hydrology, sediment transport, geomorphology, ecology, water quality, and deltaic systems. The Mississippi River Basin (MRB) of the United States was used as the backdrop and context for this synthesis because it is a continental-scale river system with a total annual water discharge similar to the Mekong River, has been highly engineered over the past two centuries, and the effects of engineering have been widely studied and documented by scientists and engineers.

The MRB is controlled and regulated by dams and other river-engineering structures. These modifications have resulted in multiple benefits including navigation, flood control, hydropower, bank stabilization, and recreation. The Mississippi River and its tributaries serve as a major transportation route, and a stable, uniform, deeper channel is needed for efficient navigation of the river. Channelizing and stabilizing the Mississippi and Missouri Rivers were monumental tasks, requiring extensive modifications to stabilize the freely meandering river channels and banks and create a self-scouring channel for navigation by reducing channel width and complexity. Flood control in the MRB is accomplished through a complex combination of levees to confine and separate the river channel from the flood plain, engineered floodways to reduce flood stages near critical infrastructure, channel straightening to increase the conveyance capacity of the channel, and the construction of dams on the tributaries to attenuate flood peaks and store irrigation water.

Dams and river engineering in the MRB have afforded the United States substantial socioeconomic benefits; however, these benefits also have transformed the hydrologic, sediment transport, geomorphic, water-quality, and ecologic characteristics of the river and its delta. The parts of the MRB with the most altered hydrology are the middle and lower parts of the Missouri River, where large main-channel dams have substantially reduced the annual peak floods, increased base discharges, and reduced the overall variability of intraannual discharges. In the upper Mississippi River, the extensive series of locks and dams has raised the stage of low-magnitude discharges but has not altered high-magnitude peak discharges. The extensive system of levees and wing dikes throughout the MRB, although providing protection from floods, has reduced overall channel capacity for high-magnitude discharges, causing increases in flood stage by up to 4 meters since construction was completed.

The primary source of sediment to the Mississippi River system is the Great Plains region, drained by three primary tributaries: the Missouri River, the Arkansas River, and the Red River. Prior to major engineering, the estimated average annual sediment load of the MRB was approximately 400 million metric tons. The construction of large main-channel reservoirs on the Missouri and Arkansas Rivers, sedimentation in dike fields, and protection of channel banks by revetments throughout the basin have reduced the overall sediment load of the MRB by more than 60 percent. Sand dredging operations and improvements in agricultural conservation practices also are implicated in the decline of overall sediment yields.

The primary alterations to river-channel morphology by dams, dikes, and revetments in the MRB have been (1) channel simplification and reduced dynamism; (2) lowering of channel-bed elevation; and (3) disconnection of the river channel from the flood plain. Prior to major human modification, many locations in main-stem channels of the Mississippi River system were more complex and dynamic, exhibiting substantial planform alignment shifts from year to year that resulted in a physically and biologically diverse channel and flood-plain structure. Channel simplification has been accomplished through a combination of river-channel shortening (reduction in curvature) and consolidation of multiple channel threads to a single channel. Channel-bed lowering has resulted from a reduction in sediment supply below main-channel dams, flow concentration by wing dikes, and localized dredging. The construction of levees, in combination with lowering of the riverbed elevation and, in some locations, the reduction of peak discharge magnitudes, has resulted in a disconnection of as much as 90 percent of the flood plain from the main channel of the Mississippi River and its primary tributaries except during extreme floods.

The freshwater discharge of the Mississippi River and its associated sediment and nutrient loads have strongly influenced the physical and biological processes in the northern Gulf of Mexico over geologic time and past centuries, and even more strongly during the last half of the 20th century. Ninety percent of the nitrogen load reaching the Gulf of Mexico is from nonpoint sources with about 60 percent from fertilizer and mineralized soil nitrogen. Much of the phosphorus is from animal manure from pasture and rangelands, followed by fertilizer applied to corn and soybeans. Increased nutrient enrichment in the northern Gulf of Mexico has resulted in the degradation of water quality as more phytoplankton grow, which increases turbidity and depletes oxygen in the lower depths creating what is known as the “Dead Zone.” In 2002, the Dead Zone extended over 22,000 square kilometers, an area similar to the size of the State of Massachusetts.

Changes in the discharge regime caused by engineered structures have direct and indirect effects on the fish communities. The navigation pools in the upper Mississippi River have aged, and these overwintering habitats, which were created when the pools filled, have declined as sedimentation reduces water depth. Reproduction of paddlefish may have been adversely affected by dams by impeding access to suitable spawning habitats. Fishes that inhabit swift-current habitats in the unimpounded lower Mississippi River have not

declined as much as those in the upper Mississippi River. The decline of the endangered pallid sturgeon may be attributable to channelization of the open river below St. Louis, Mo. The Missouri River supports a rich fish community that remains relatively intact. Nevertheless, the widespread and long history of human intervention in river flow has contributed to the declines of about 25 percent of the species.

The Mississippi River Delta Plain is built from six delta complexes that were constructed over 6,000 to 8,000 years. These complexes form a massive area of coastal wetlands, which support the largest commercial fishery in the conterminous United States. Since the early 20th century, approximately 4,900 square kilometers of coastal lands have been lost in Louisiana. One of the primary mechanisms of wetland loss on the Plaquemines-Balize complex is believed to be the disconnection of the river distributary network from the delta plain by a massive system of levees, which prevent overbank flooding and, hence, the replenishment of the delta top by sediment and nutrient deliveries. Other mechanisms of wetland losses include the substantially reduced sediment deliveries from upstream reservoir construction, canal dredging, human-enhanced saltwater intrusion, and enhanced land subsidence. Efforts by Federal and State agencies to conserve and restore the Mississippi River Delta Plain began over three decades ago and have accelerated over the past decade because of growing awareness of the implications of global sea-level rise and the importance of coastal wetlands as a natural protection from storm surge in Louisiana coastal communities. Regardless of these efforts, however, land losses are expected to continue because upstream sediment supplies are not sufficient to keep up with the projected depositional space being created by the combined forces of delta plain subsidence and global sea-level rise.

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