SEVEN

The Mississippi: Once and Future River

The Mississippi River basin encompasses the tremendous natural diversity of the continental United States. The headwaters of the various subbasins spread from the Appalachian Mountains of the east across the forests of the central-northern United States and the grasslands of the western Great Plains to the Rocky Mountains. This huge span includes humid continental, semiarid steppe, and wet subtropical climates. The river is the center of this drainage basin that encompasses 3.5 million square kilometers and 41 percent of the contiguous forty-eight states.

Peak annual discharge averages 39,300 cubic meters per second at Vicksburg, Mississippi. The river splits into distributary channels some kilometers farther downstream from this point, and these combined channels discharge an average of 580 cubic kilometers of water a year to the Gulf of Mexico. This is the seventh largest river discharge to the ocean, but the Mississippi is unpredictable. In 1954 the river peaked at only 19,800 cubic meters a second at Vicksburg, whereas in 1927 it peaked at 64,000 cubic meters a second. No single flood has ever encompassed the entire Mississippi basin.

From the western half of the basin comes the sediment that keeps the river a turbid brown. From the northern and eastern portions comes the water. The heaviest precipitation falls from spring thunderstorms triggered by warm, humid air moving northward from the Gulf of Mexico. But winter frontal storms and rains during summer and

autumn contribute to totals that vary from 80 centimeters in the northern part of the upper basin to 114 centimeters in southern Illinois and 150 centimeters in parts of Tennessee.

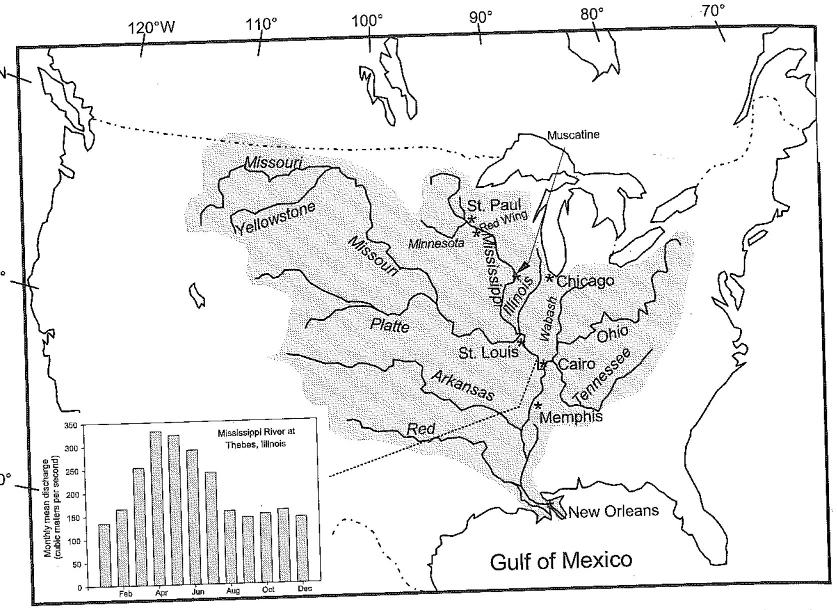
The Upper Mississippi

The snowmelt and rainwater collect perceptibly at Minnesota's Lake Itasca, which is accorded the honor of being the headwaters of North America's largest river. Although the name Itasca sounds vaguely Native American, it was created by Henry Schoolcraft when he traced the Mississippi upstream to the small lake in 1832 as part of an expedition by the U.S. War Department. Itasca comes from the Latin *veritas caput*, "true head." Despite Schoolcraft's assertion, others quibble that the true head of the river is at Little Elk Lake, eight kilometers above Itasca. And then there are those who argue that the headwaters of the Mississippi's tributary, the Missouri, having the longest journey down to the Gulf, should be considered the source.

Average velocity along much of the Mississippi's length is five to seven kilometers an hour, about the pace of a fast walk. Despite this seemingly unimpressive rate of flow, it takes only a little more than thirty days for the average drop of water to travel from Lake Itasca to the Gulf of Mexico. Along this four thousand kilometer trip more than 250 tributary rivers add their waters to the main channel, speeding the water drop on its way.

The placid waters of Lake Itasca overflow across a bouldery sill to begin their downstream journey as the Mississippi River. The narrow stream channel winds slightly as it moves north and then east across a lightly populated landscape covered with bogs and spruce forests. The eight hundred kilometer headwaters portion of the river descends 200 meters from an elevation of 440 meters above sea level at Itasca's outlet to St. Anthony Falls. Natural falls and rapids, and nine glacially formed lakes, punctuate this headwaters portion of the river. Beyond Itasca, the river grows more sinuous as the valley widens. Small rapids separate wetlands dotted with beaver lodges, cranberry bogs, and beds of wild rice from natural lakes and artificial impoundments.

The river follows a circuitous course through greater and lesser lakes—Bemidji, Cass, Winnibigoshish—slowly changing course toward the southeast. The headwaters portion is so sinuous that a third of the river's entire length is in Minnesota. Seen from the sky, the viewpoint of millions of migratory waterfowl, this portion of the river basin is a



7.1 Location map for the Mississippi River drainage basin (shaded), with principal tributaries and cities labeled. Inset figure shows a sample hydrograph with the average monthly flow at Thebes, Illinois, just upstream from the junction with the Ohio River.

green-and-blue mosaic of wetlands, mixed conifer and deciduous forests, grasslands, and thousands of ponds and small lakes. The blue river moves sinuously across this mosaic, as though aiming to touch every watery depression along its route.

These depressions are an inheritance of the enormous continental ice sheets that advanced and retreated four times during the past two million years. Unlike the headwaters of most great rivers, no mountains create precipitous slopes that rush the Mississippi onward. The last great geologic force shaping this landscape was the final advance of the continental ice sheet, which reached its farthest southward extent about fourteen thousand years ago. Each time an ice sheet nearly two kilometers thick flowed southward, its great weight depressed Earth's crust. Meltwater ponded beneath the massive ice, breaking out periodically in catastrophic floods that sculpted the landscape so thoroughly that their routes can still be traced today. Some of these floods discharged volumes of water comparable to the 1993 flood, the largest flood ever recorded on the Upper Mississippi.

When it retreated, the ice released massive quantities of sediment. Rivers of meltwater flowing beneath the ice sometimes arranged the

sediment in neatly sorted, linear mounds called eskers. Braided rivers beyond the ice front deposited sand and gravel across broad plains. Huge chunks of ice left behind as the glacier receded were buried and insulated by this sediment, so that when they finally melted, the overlying sediment collapsed into the resulting depression to create a kettle lake. The history of glacial deposition can be traced in the modern bed of the Mississippi as the river flows alternately over boulders, bedrock, mud, and sand.

Along much of the ice front, the melting ice simply dumped sediment in long lobes called moraines. The depressed Earth rebounded more slowly than the ice sheet melted, so that for a time the land sloped back toward the center of the ice, allowing the moraines to effectively trap enormous volumes of water melting from the ice sheet. The retreat of the most recent ice sheet blocked its own drainage into Hudson Bay, creating Lake Agassiz. This lake, hundreds of kilometers wide and nearly sixteen hundred kilometers long from northwest to southeast, episodically overflowed into the Glacial River Warren. River Warren cut the valleys now occupied by the Minnesota River and the Mississippi below the Minnesota's mouth at the southern end of the Minneapolis–St. Paul metropolitan area. The Lake Agassiz overflows produced floods two to ten times the size of the 1993 flood.

The Mississippi first appeared about five hundred thousand years ago, cutting a valley into sedimentary rocks as it flowed along the edges of an earlier ice sheet. The river system persisted through an interglacial period and then was partially overwhelmed by the most recent ice sheet, which formed Lake Agassiz as it began to retreat. Each overflow from Agassiz into the River Warren sent such a pulse of cold freshwater down to the Gulf of Mexico that isotope contents of marine sediments clearly record the influx. As the ice sheet retreated back into Canada, the Great Lakes, the Hudson River, and the St. Lawrence River were progressively uncovered, and some of the meltwater began to flow into the North Atlantic Ocean through these alternative routes. So much freshwater flowed into the North Atlantic that scientists believe it temporarily shut down the Great Ocean Conveyor Belt that modulates climate in the higher latitudes.

The meltwater of the great ice sheets has long since drained back to the oceans to resume its endless cycling between ocean, land, and atmosphere. But the irregular topography and poorly drained soils left by the ice sheets still store the precipitation that falls west and south of the Great Lakes, releasing the water slowly into springs and rivers that ultimately feed the Mississippi.

The first Europeans to reach this region were French fur trappers seeking to profit from the abundant beavers. Driven by commerce and curiosity, the *coureurs de bois*, "runners of the woods," explored much of the upper watershed and main channel within a period of only thirty years between the 1650s and 1680s. Britons and then Americans subsequently dominated the fur trade in the Upper Mississippi region. By the late 1800s, the original beaver population of the Mississippi River basin, estimated at ten to forty million animals, was nearly gone. Removal of millions of beavers, and the dams they built, likely reduced local overbank flooding and the extent of wetlands in the upper basin, making it that much easier for loggers and farmers to follow the fur trappers.

The fur trade moved west into the Rocky Mountains as the beavers were trapped out of the northern Midwest and the Upper Mississippi basin, and people began to look about for the next resource that could be exploited. Commercial logging began in the 1820s, subsequently aided by rapid expansion of the railroad network. Numerous commercial sawmills competed for the wood coming down the river in great lumber rafts as large as 1.2 to 1.6 hectares. As historian R. D. Tweet wrote, "Down this river, between 1835 and 1915, came virtually every usable white pine log in the states of Minnesota and Wisconsin." Some of the earliest engineering modifications to the Upper Mississippi were undertaken in connection with log floating. Wing dams of piled stone constricted the channel and prevented the logs from spreading out across the floodplains or into secondary channels. Naturally occurring snags and other obstacles were blasted or dredged. Like the removal of beavers, these changes reduced the extent of flooding and wetlands in the valley bottoms.

Farmers quickly moved in, although diversified farming was only marginally successful in the cutover areas of the Upper Mississippi watershed during the nineteenth and early twentieth centuries. Today the primary regional industries continue to be logging and farming, as well as recreation. Farming becomes more widespread downstream, and the river picks up progressively more sediment along its route as erodible croplands replace stable forested lands. These effects were even more dramatic in the recent past. Increasing deforestation and agriculture in the upper portion of the Mississippi drainage during the nineteenth and early twentieth century produced so much excess sediment that rivers and streams throughout the drainage lost some of their ability to convey water downstream as channels clogged up. Combined with decreased infiltration capacity and increased runoff from the denuded

slopes, these changes produced larger floods in many of the drainages tributary to the Mississippi. (Knowledge of these changes helped to fuel the argument that deforestation in the Himalaya might exacerbate flooding lower in the Ganges.) Flooding, erosion, and sediment deposition on floodplains have all decreased since the mid-twentieth century in response to better land conservation practices, but the Mississippi today has already taken on its trademark muddy brown as it flows into Minneapolis and St. Paul, Minnesota.

The twin cities lie well up the Mississippi River basin, nearly forty-two hundred kilometers upstream from the river's mouth at the Gulf of Mexico. Yet the river is already impressively large thanks to the consistent rain and snow of the uppermost basin. Here the Mississippi becomes, briefly, an urban river. Concrete and stone riprap lines the rigidly channelized banks. Roads and railways crowd the banks, and storm sewers drain contaminants into the brown water.

The Twin Cities metropolitan area is one of the principal sources of heavy metals such as lead and mercury, insecticides, and polychlorinated biphenyls (PCBs) in the Upper Mississippi. Although improved municipal water treatment and changes in industrial practices have reduced levels of mercury and lead since the 1970s, other contaminants such as PCBs remain widely distributed. PCBs are a very stable group of industrial chemicals that leach into the river primarily from urban and industrial areas. They were used for electrical transformers and capacitors, among other things, until banned in the United States in 1979. When the U.S. Geological Survey studied contaminants in the Mississippi River during 1987–92, they found PCBs in almost every silt sample taken throughout the river basin. Survey scientists found comparable PCB concentrations in the tissues of catfish. Most of the PCBs moving insidiously through the Mississippi River drainage are attached to clay and silt particles. Where clay and silt settle out of suspension in backwaters or on the floodplain, the PCBs settle with them and become concentrated. PCBs entering the Mississippi from St. Paul and Minneapolis ride downstream on silt and clay particles until the sediment is mostly trapped and stored in Lake Pepin. Concentrations of contaminants are generally smaller just downstream from the lake and remain so until the entry point of the next contaminant source.

PCBs are linked to birth defects, reproductive failure, liver damage, tumors, a wasting syndrome, and death, both in humans and in other living creatures. These contaminants bioaccumulate within an organism and biomagnify as organisms pass on their accumulated doses through the food web. Invertebrates that ingest sediment to get at the bits of organic detritus mixed in with the silt and clay ingest PCBs and other contaminants as well, then pass them up the food chain. Because PCBs are very stable and slow to chemically degrade under environmental conditions, they accumulate in the environment.

Pollution-sensitive mayflies disappeared from parts of the Mississippi by 1927, including the stretch downstream from the Twin Cities and Lake Pepin, then reappeared by 1984 as water quality began to improve. In areas that remain too polluted, mayflies are replaced by pollution-tolerant organisms such as midges. In *Immortal River*, Calvin Fremling compares *Hexagenia* mayflies to canaries in a coal mine. Just as miners used the sensitive canaries to detect poisonous, odorless gases, so the distribution of mayflies along rivers reflects the distribution of contaminants. Burrowing mayfly nymphs live in sediments where contaminants can accumulate. The mayflies cannot swim long distances to escape environmental stress from toxins in the sediment or from low oxygen levels, so although their presence does not mean that the river is unpolluted, it does indicate that some minimum level of water quality has been maintained for the mayfly's life span of up to a year.

When they are present, mayflies efficiently convert organic muck on the streambed into their own adult bodies, which provide high-quality food for fish and birds. The bottom-feeding mayfly nymphs unfortunately also concentrate organochlorine compounds and heavy metals that predators ingest with the nymphs. Digging by nymphs can also resuspend contaminants that might otherwise remain segregated in streambed sediments. Mayfly nymphs might not sound like a particularly disruptive force in a river the size of the Mississippi, but the sheer number of insects makes their burrowing significant: as mayflies returned to the waters of Lake Erie, *Hexagenia* adults formed clouds twenty-three kilometers long and over six kilometers wide that were observed on Doppler radar.

Downstream from the twin cities, the Mississippi winds among a maze of loosely woven channels, islands, and wetlands. Low buff cliffs of crumbling sandstone, shale, and limestone represent the great ancient oceans and sedimentary basins characteristic of the upper Midwest. The river has carved a broad, flat valley among the bluffs and ridges of the undulating uplands, and the wetlands and sloughs record the meandering passage of the river through time.

By the time it reaches Red Wing, Minnesota, the river has flowed 80 kilometers southeast and passed through two lock and dam complexes. Today the Upper Mississippi drops only eighty meters along the

3,170 kilometers of its course between St. Anthony Falls and its junction with the Missouri. Like much of the Danube, the Upper Mississippi is a tamed river, moving in measured lockstep between the twenty-nine locks and dams along these 3,170 kilometers. On a global compilation of intensity of flow regulation, the Mississippi basin is colored a vivid red for strongly impacted.

Like many place-names along the river, Red Wing derives from Native American inhabitants. In many cases the language of indigenous peoples as reflected in place-names is all that now remains of their traditional culture. "Mississippi" comes from a native language. Some authors trace the name's origin to a Chippewa word meaning Father of Waters, whereas others trace it to an Ojibwa word meaning Big River. Of the ten states bordering the Mississippi, only Louisiana (named for France's Louis XIV) does not take its name from a Native American word.

Scattered roads, farm fields, and houses lie superimposed on the varied landforms created by the Mississippi across the bottomlands around Red Wing. Like the Amazon today, the Mississippi historically had large tracts of seasonally flooded forest. A wide variety of organisms used these forests: migrating or seasonal birds such as the North American wood duck (*Aix sponsa*), fish such as black bullheads (*Ictalurus melas*) or orangespotted sunfish (*Lepomis gibbosus*), Blanding's turtles (*Emydoidea blandingii*) and other reptiles, amphibians including the amphiuma, a salamander a meter or more long, and invertebrates that scientists may not yet have even identified. Early travelers describe catfish big enough to overturn a canoe and flocks of waterfowl darkening the sky as they passed. Big floods coming through at intervals recontoured the riverbanks, ripping out mature trees and leaving fresh sediment in which seedlings could germinate, creating a continually changing forest with age and species composition structured by the dynamics of the big river. More than 80 percent of the floodplain is still connected to the river along the Upper Mississippi between the headwaters and the junction with the Ohio River, although much of the floodplain forest has been cleared. The riverbanks remain thickly wooded, but in many places the trees form only a fringe, with cleared lands beyond.

Environmental historians debate how extensive the forests of the northeastern quarter of the United States once were. The old adage that a squirrel could travel from the Atlantic coast to the edge of the central prairies without touching the ground has been called into question by research indicating that Native Americans used fire extensively to create more open, parklike woodlands favored by game such as deer. Some

7.2 Riverbank vegetation and wetlands along the upper Mississippi. Here a thin fringe of shrubs and trees separates the main channel from a floodplain wetland, with a denser forest beyond. Although less common today, this mosaic of bottomland forest and wetlands once extended for hundreds of kilometers along the river.

of this research relies on pollen and sediment deposited in lakes, some uses historical accounts. The Englishman Jonathan Carver described intermixed stretches of prairie along the Mississippi between the junction of the Wisconsin River and Lake Pepin during his travels in 1766. Zebulon Pike also described prairies with groves of fire-resistant trees such as bur oak (*Quercus macrocarpa*) during his 1805 journey upstream from St. Louis, as did Henry Schoolcraft in 1820 (Pike 1810; Schoolcraft 1953). Forests of more fire-sensitive trees such as sugar maple (*Acer saccharum*) grew in deep, moist valleys and on north-facing slopes. A mix of fire-resistant and fire-sensitive trees grew along the floodplains. Regardless of the local density of the Upper Mississippi River basin forests, the forests supplied plentiful wood to the river, creating large logjams that enhanced overbank flooding, as well as the partly buried logs that snagged and sometimes sank passing boats.

Navigation on the big river and many of its tributaries was notoriously difficult during the first decades of the nineteenth century. Navigators had to thread their way among numerous side channels and

backwaters where the river split around hundreds of natural islands. In summer, low flows and shifting sandbars limited depth even in the main channel. Logs partially anchored in the streambed formed obstacles that could rip the hull out of a large steamboat. Charles Dickens penned a particularly vivid description of these snags during his steamboat trip in the early 1840s. "[The Mississippi] running liquid mud, six miles an hour: its strong and frothy current choked and obstructed everywhere by huge logs and whole forest trees: now twining themselves together in great rafts . . . now rolling past like monstrous bodies, their tangled roots showing like matted hair; now glancing singly by like giant leeches; and now writhing round and round in the vortex of some small whirlpool, like wounded snakes."

Dead trees floating down the river might snag on a sandbar or a bend of the channel, forming a larger obstacle that snagged more wood floating downstream. These logjams grew to formidable size and would quickly reform once they were cleared. Logjams were ubiquitous on the Mississippi's tributaries from the upper Ohio River, where John Bruce began removing snags in 1825, to the Red and Atchafalaya rivers in Louisiana. When first described in 1803, the Atchafalaya was choked with logs that prevented boatmen from following the river's shorter course to the Gulf of Mexico. Repeated efforts to clear the channel starting in 1812 produced only temporary navigation access. One enormous logjam nearly 170 kilometers long on the Red River withstood repeated attempts at clearing, despite a six-year effort during the 1830s by Henry Shreve, a steamboat captain who invented a steam-powered "snag machine" that speeded up the laborious process of removing tangled masses of logs from the river. Shreve's long effort temporarily cleared the jam, which then reformed and persisted until the 1850s. The logs blocking navigation along the Atchafalaya finally were thoroughly removed in 1880.

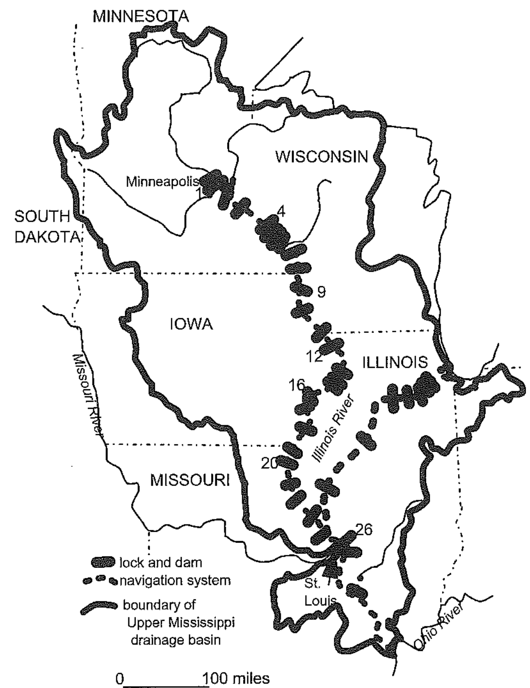
The big logjams did more than impede navigation. By also impeding the downstream movement of floodwaters, they helped to sustain extensive floodplain wetlands that supported a wealth of plants and animals throughout the Mississippi River drainage. Once the logjams were removed, floodwaters spilled out of the riverbanks less frequently and for shorter periods, and the extent of wetland vegetation shrank. In places the energetic floodwaters enlarged the river channels. Once the jams were removed, animals ranging from fish to wading birds lost some of their quiet-water habitat. The combined effects of beaver trapping, modifying channels for log floating, and removing logjams tended to reduce the complexity and flooding of the bottomlands, thus lessening the amount and diversity of habitat available to a wide variety of species.

Shackles for a Giant

Beyond Red Wing, the current of the Mississippi slows as the river enters Lake Pepin. The lake originally formed about ninety-five hundred years ago when a large delta from the tributary Chippewa River partially blocked the Mississippi valley. Although lock and dam complexes are now present above and below Lake Pepin, the delta of the Chippewa River remains a primary control on lake level. The U.S. Army Corps of Engineers regularly dredges the lake because of large annual inputs of sand from the Chippewa River. Attempts to stabilize or flush sediments from Lake Pepin and backwaters above each lock and dam complex must be undertaken with care, for the sediments stored in pools upstream from every lock and dam of the Upper Mississippi have elevated concentrations of heavy metals.

Lake Pepin is now less noticeable as an interruption of the river than it would have been historically because of the reservoirs created by water ponded upstream from each of the numerous lock and dam structures along the river. The sequence of locks and dams along the upper river, which a 1970s Corps of Engineers promotional film described as shackles for a giant, is designed to maintain a minimum water depth of 2.7 meters (nine feet) in the main channel used for boat navigation. The channelization has been carried much further in the Lower Mississippi, where the floodplains and secondary channels are largely disconnected from the main river. Instead of completely channelizing the upper and middle portions of the Mississippi in a similar manner, decades of engineering have focused on creating and maintaining a central navigation channel.

The Upper Mississippi River historically had a distinct seasonal pulse of high flows during March to May and low flows during August to October. These summer and autumn low flows made navigation difficult, if not impossible, and channel modification quickly followed the first steamboat that forged its way upstream to St. Anthony Falls in 1823. Within a year, the U.S. Army Corps of Engineers began removing snags, dredging sandbars, excavating the rocks that formed rapids, and damming sloughs to keep the water within the main channel. Natural processes would have kept the Corps sufficiently busy maintaining a waterway for the shallow-draft steamboats, but land clearing and



7.3 *Above*, downstream from a lock and dam along the upper Mississippi River. As on the Danube, these navigation dams substantially alter the seasonal fluctuations of river flow, store sediment, impede the movement of fish along the river, and alter habitat available for plants and animals. *Below*, the navigation system of the upper Mississippi River basin, showing lock and dam complexes on the Mississippi and major tributaries. (After Changnon 1996, figure 5-1.)

agriculture accelerated the rush of sediment from the hill slopes into the river.

Steamboat traffic on the upper river reached its peak during the 1850s and 1860s with increasing immigration and the shipment of agricultural products such as wheat to railheads on the river's eastern bank. As more sediment came in and boat drafts grew larger after the 1860s Civil War, the Corps ramped up its efforts to channelize the Mississippi for navigation from the mouth of the Ohio River upstream to Minneapolis. Railroads reduced steamboat commerce during the 1860s to 1890s except for lumber being rafted downstream. Congress nonetheless authorized maintenance of a navigation channel that grew successively deeper, from 1.2 meters in 1866 to 1.4 meters in 1878 and 1.8 meters in 1907. This channel was created through nearly continual dredging combined with use of "closing dams" that blocked the river from entering side channels and wing dams that constricted the flow, increased the current, and thus encouraged "natural" dredging.

Barge traffic on the Upper Mississippi waxed and waned following completion of a 2.7 meter channel in 1940. Subsequent proposals to enlarge the channel have been defeated. The Corps has also considered altering lock and dam operation in a climate of stable or declining grain shipments, competition for midwestern grain from other navigation routes such as the St. Lawrence Seaway, and growing environmental concern about the negative side effects of navigation improvements. Historians and economists question the necessity of spending hundreds of millions of dollars in tax subsidies and navigation projects to sustain a barge industry that exists primarily to ship grain overseas. Although Congress instituted user fees in 1978 for barges taking advantage of federal engineering, these fees do not begin to cover the full cost of maintaining the navigation channel.

The numerous locks and dams along the Upper Mississippi finally transformed the seasonal pulses of the river's flow into a more sluggish current between a series of shallow impoundments that now occupy some of the historical river floodplain. The locks and dams fulfill their purpose of creating more uniform water depths that make navigation easier, but as on the Danube, they also have many unintended effects on the plants and animals living along the river corridor.

The seasonally flooded and exposed wetlands along the 1,420 river kilometers between St. Paul and Cairo, Illinois, historically supported millions of fish, birds, reptiles and amphibians, invertebrates, and mammals. Although the ponded water above each of the dams between St. Paul and Alton, Illinois, now attracts migrating ducks, the water

also floods part of the historically seasonal wetlands year-round, creating greater water depth, turbidity, and sedimentation as the slowing current deposits some of the sediment it carries. Increased depth and sedimentation have killed the aquatic plants many aquatic organisms feed on.

To mitigate these side effects, the Nature Conservancy is working with the Corps of Engineers, experimenting with several techniques. These include dredging the lakes formed above dams to reduce sediment thickness and adding islands built from the dredged sediment to create shallow water. Backwater isolation projects involving dike construction, pump installation, and management of water levels are used to produce food or nesting areas for migratory waterfowl or habitat for fish. Flow is introduced to other backwaters to counteract oxygen depletion. Engineers actively replant aquatic plants and create periodic reductions in water level in some pools above dams as a means of compacting and dehydrating sediments and restoring vegetation. The success of local experiments with lower summer water levels above dams is encouraging, but such efforts are constrained by navigation requirements and access to riverside docks for commercial and navigational boaters. Because federal law mandates that the Corps maintain the 2.7 meter deep, 91 meter wide navigation channel from Minneapolis to south of St. Louis, restoring floodplain wetlands through seasonal drawdowns may not be feasible during low-water periods. As on the Danube, the basic requirements of contemporary navigation severely limit the scope of restoration efforts, but even limited efforts to restore some of the form and function present before river engineering can make a difference for declining fish and bird populations.

Fish of the Mississippi

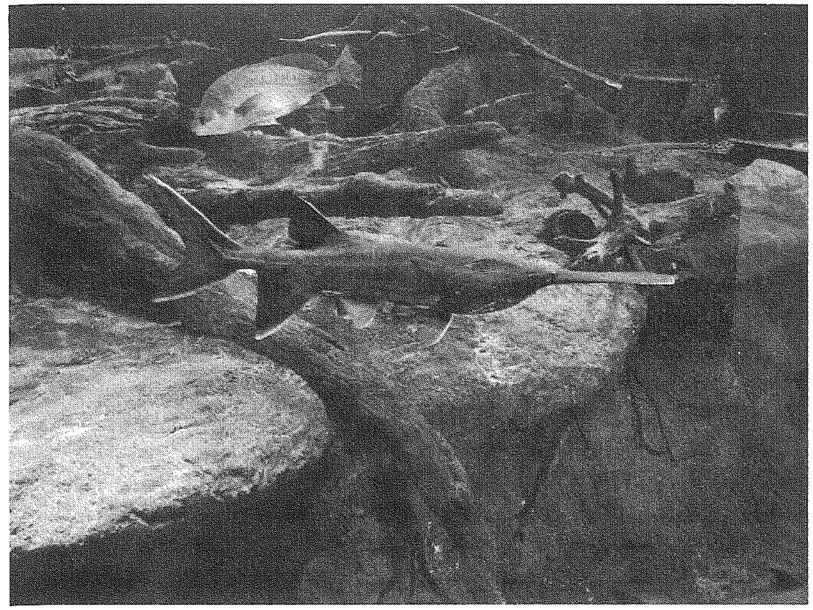
Downstream from Lake Pepin, the width of the channel alternately expands and contracts among numerous islands. More than five hundred islands divide the channel between St. Paul and St. Louis. Beyond the sandy, wooded banks lie the extensive riparian wetlands of the Upper Mississippi National Fish and Wildlife Refuge. The refuge was established in 1924 to protect populations of smallmouth bass but is now managed primarily for migratory waterfowl.

More than three hundred bird species, including 60 percent of the species in North America, use the river corridor. Every spring and fall millions of birds migrate along the Mississippi or remain as year-round residents. The river's north-south orientation and nearly continuous habitat are critical to the life cycle of these birds. The Mississippi flyway draws birds across a broad band from northern Alaska to Baffin Island and funnels them down the river valley, creating a winged river above the liquid one.

As exemplified in the creation of the Upper Mississippi National Fish and Wildlife Refuge, initial attempts to protect fish populations along the Mississippi focused on game fish such as bass. Attention has gradually shifted toward native species as scientists realize that many of the turbid river's miraculously adapted fish are now at a disadvantage in a world of regulated flows, limited floodplain access, and locks and dams. Among these are paddlefish.

Paddlefish (*Polyodon spathula*) in the Mississippi River historically grew to at least 1.8 meters and ninety kilograms. Part of their size derived from longevity. The fish can live at least thirty years, feeding almost constantly and continuing to grow as long as they live. They are fish to match the big river. They swim eight hundred kilometers to spawn and can travel at five kilometers an hour against a current running at the same rate. Yet, like most whales, these big fish live on very small food organisms. Up to a third of a paddlefish's body length consists of a broad, rigid flattened snout containing tens of thousands of minute electroreceptors. Paddlefish adapted to the murky waters of the Mississippi by evolving these sensitive receptors to detect the tiny electrical signals generated by zooplankton measuring only a fraction of a centimeter. A paddlefish swims along with its mouth open, using sievelike gill rakers within the mouth to filter zooplankton from the water and suspended sediment.

Despite these adaptations to life in a turbid river, and the species' endurance in North America for 140 million years, fisheries biologists estimate that by the 1980s paddlefish populations in the Mississippi drainage basin had fallen to 10 to 20 percent of historical levels. Commercial fishing for paddlefish caviar was a major culprit in the decline, as was habitat loss. Siltation under the ponded water of reservoirs destroyed spawning areas. Dams reduced upstream and downstream movement of the migratory fish. Channelization mostly eliminated backwater areas important to both young and adult paddlefish and removed the zones of low velocity where paddlefish feed on zooplankton drifting downstream. The passage of a large commercial vessel creates a two- to three-minute recession in water level along a river shoreline that can strand young paddlefish. Turbulence from the vessel's passage kills paddlefish larvae. The beautifully adapted electroreceptors that



7.4 Paddlefish in an aquarium at the National Mississippi River Museum and Aquarium. This superbly adapted native fish is now uncommon in the river but can be seen along with other native species at this museum in Dubuque, Iowa.

detect swarms of tiny zooplankton are swamped by the signals returned from the large metal gates of locks and dams, which the paddlefish try to avoid.

The continued presence but precarious status of paddlefish in the Mississippi is an example of what drives the hopes and anxieties of fisheries biologists. On the one hand, the Upper Mississippi remains quite sinuous despite more than a century of river engineering, and the pools behind the locks and dams provide reasonably complex shorelines beyond the navigation channel. On the other hand, fisheries biologists recently predicted that unless management action is taken, within fifty years the Upper Mississippi River will consist of a main channel bordered by dry land with few shallow marshes and will support limited diversity and abundance of fish. There is much at stake. The habitat diversity associated with the main channel and numerous backwaters supports an entire fishy world. A total of 306 species of fish are known to inhabit various parts of the Mississippi River basin. The river supports an unusually high number of species relative to other large rivers in the temperate zones because the river network is physically complex, with a wide range of aquatic habitats such as backwaters and floodplain lakes. The north-south orientation of the river basin also provided a corridor for escape and subsequent recolonization during glacial advances and retreats.

As on most big rivers, on the Mississippi fish species diversity increases downstream. The headwaters from Lake Itasca to St. Anthony Falls are home to sixty-seven species. The falls were historically an important barrier to upstream fish migration, and the terrain of the upper river was liberated from the glacial ice relatively recently. Headwaters fish must contend with shifting sediments on the streambed, boggy corridors and areas of dense aquatic vegetation, and periodic very low flows. Fishing and other disturbances have been minimal, and fish communities appear to be largely the same as they were in the late 1800s.

From St. Anthony Falls downstream to the Mississippi's junction with the Missouri, 132 fish species are present, and 114 species live in the river segment between the mouth of the Missouri and the mouth of the Ohio. The distribution of these fish also reflects natural barriers such as rapids, falls, and lakes. About half of the species present downstream from St. Anthony Falls simply cannot continue upstream past the falls. Those that can go upstream are mostly lake species that were able to cross drainage divides when glacial lakes connected the headwaters with the St. Croix River and the Red River of the North. Completion of the locks at St. Anthony Falls in 1963 opened another stretch of river to intrepid fishy pioneers.

Channelization and navigation development and pollution have also affected fish communities in the Upper Mississippi. Dam number 19, which is especially high because it is operated for hydropower, prevents upstream migration of many fish species. The ponded water upstream of locks and dams provides habitat for some species, but this is gradually being lost through sediment accumulation. The pool behind lock and dam number 19 has lost 55 percent of its original volume through sedimentation in the years since it was closed in 1913.

Several of the lock and dam complexes create anoxic zones where oxygen dissolved in the water drops to levels that are dangerously low for fish and other aquatic organisms. When lock and dam number 1 was completed in 1917, it collected most of the raw sewage of Minneapolis and St. Paul. Lock and dam number 2, completed in 1930, collected the rest. A Bureau of Fisheries study during August 1927 found that seventy kilometers of the river downstream from St. Paul lacked sufficient oxygen to sustain any fish life. Although sewage contamination has now been reduced by better treatment facilities, the drop in

number of fish species from 132 upstream to 114 between the Missouri and Ohio junctions may reflect the extensive channelization and levees that restrict habitat extent and diversity. Habitats in the upper and middle reaches of the Mississippi now include both naturally occurring features such as sloughs and tributary mouths and engineered features such as tailwaters, navigation pools, and areas of slower flow near rockwing dikes.

The entry of Missouri River waters into the Mississippi further affects fish species distributions. Species such as walleye that are less tolerant of turbidity are not common below the mouth of the sediment-laden Missouri. On the other hand, the Missouri contributes several species such as pallid sturgeon (*Scaphirhynchus albus*), western silvery minnow (*Hybognathus argyritis*), plains minnow (*Hybognathus placitus*), and various species of chub (*Macrhyobopsis* spp.) that are restricted to the middle reaches of the Mississippi.

Yet another significant influence on fish species distribution along the Mississippi is the introduction of exotics. Common carp (*Cyprinus carpio*), grass carp (*Ctenopharyingiodon idella*), rainbow smelt (*Osmerus mordax*), goldfish (*Carassius auratus*), striped bass (*Marone saxatilis*), and other exotic species have been introduced to the middle reaches of the river. Fish stocking began in 1872 along the upper river. Carp introduced themselves during the 1880s. Carp are highly efficient at feeding on the plankton also eaten by species such as paddlefish. Common carp became a major component of the commercial fishery in the river, reaching a mean annual harvest value of $270,000 between 1953 and 1977. During the succeeding decade the carp began to decline, partly because of PCB contamination in areas such as Lake Pepin, and partly because of poor spawning success during high or variable water years in a river that now lacks the sheltered backwater habitats critical to larval and juvenile fish of many species. The dams for the 2.7 meter navigation channel created large amounts of new backwater habitat by flooding the center sections of the navigation pools. The shallow edges of these new backwaters are readily accessible locally from the deep main channel, however, and do not provide the shelter and limited accessibility important to young fish that need protection from predators. Lock and dam 19 at present appears to be limiting the upstream migration of some carp species, and proposals to build a fish passage around it must address the movement of the carp. The potential for migration by exotic carp, like the downstream movement of contaminated sediment in navigation pools, illustrates some of the environmental costs of rehabilitating the Mississippi River system.

The number of fish species present in the Mississippi rises to 150 in the river segment from the mouth of the Ohio downstream to the coast. None of the fish in the main river are endemic, although the tributaries include endemic species. Some of these species are in trouble. The U.S. Fish and Wildlife Service lists three species in the Mississippi drainage as endangered, but other species are under consideration for listing. NatureServe, a network of natural heritage programs, considers twelve Mississippi basin fish species imperiled. That no fish has yet become extinct provides further incentive to restore some of the natural habitats and functions along the Mississippi system while all the components of the river ecosystem remain.

Throughout the Mississippi River basin, from the smallest tributaries to the big river itself, the number of individuals and species making up fish communities has changed as a result of land use and river engineering. Fish must cope with excess nutrient inputs from fertilizer as well as toxic wastes from agricultural and urban lands. Habitat loss from channelization, levees, and dams restricts fish abundance and diversity. Many fish now rely on floodplain habitats that include depressions left by excavating sediment to build levees, water treatment lagoons, and canals, as well as backwaters present at tributary junctions and oxbow lakes formed as meander loops are cut off from the main channel during floods. Increased sedimentation from land use changes and channel engineering further limits habitat availability. Alteration of the seasonal flow of water by dams and tile drains interferes with fish movement, reproduction, and growth. Rising water temperatures from loss of riverside shading stress many fish species. The effects of contamination, habitat loss, and flow regulation are no recent revelation. Careful observers commented on changes in the Upper Mississippi watershed and the resulting changes in species composition of fish as early as the 1890s.

Very costly management actions are now being undertaken to mitigate some of these effects, although it remains to be seen whether these will prove sufficient given the magnitude and scope of the problems. The first step in rehabilitating any river is to monitor it and document what has changed from historical or reference conditions. As of 1999, scientists ranked five of six monitoring criteria as moderately impacted along the upper impounded reach of the Upper Mississippi and highly impacted along the lower impounded reach.

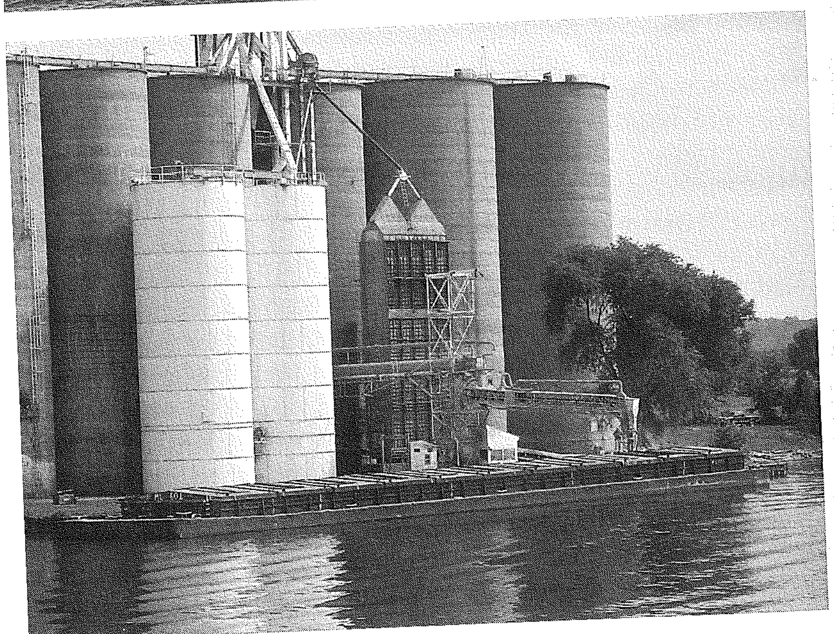
Partly in response to this type of evaluation, several federal and state agencies have come together as stakeholders in the Upper Mississippi basin to coordinate continued monitoring and restoration efforts,

including those described earlier for backwaters at locks and dams. As of 1995, site-specific habitat rehabilitation and enhancement projects were being constructed at fifty-four locations throughout the Upper Mississippi. Habitat in the main channel is restored by changing dredge disposal and modifying wing dams. Floodplain wetlands are restored by acquiring lands currently in agriculture and replanting them with native species. In each case, successful rehabilitation depends on understanding the habitats needed by plants and animals, the processes that create and maintain those habitats, and the effects that proposed manipulations of the river have on these habitats and processes. Limited funding, however, has been one of the primary constraints on efforts to restore the Mississippi River system.

Federally funded restoration programs are crucial to rehabilitating the river and to addressing the large-scale limitations to river health posed by navigation structures and maintenance or by point and nonpoint sources of contamination along the river. But citizen groups and nongovernmental organizations are also taking matters into their own hands, removing hundreds of tons of trash from the river and planting thousands of hectares of native bottomland trees along the shorelines and islands of the Mississippi. These undertakings foster a sense of stewardship and responsibility in people living along the river's course that may also generate greater political support for large-scale river restoration.

A River of Grain

Much of the historical and contemporary river engineering on the Mississippi was undertaken to maintain navigability for barges, which move along the Upper Mississippi at regular intervals. An individual grain barge is 4 meters high and 10.6 meters wide. Up to fifteen barges can be moved with one tow on the upper river, although "tow" is a misnomer given that most of the barges are actually pushed from behind by a single boat. Downstream from Cairo, Illinois, each tow is allowed to transport forty-five barges. Each barge can hold fifteen hundred tons, or the equivalent of sixty loaded semitrailers. A fifteen-barge tow thus carries the equivalent of nine hundred truckloads. Some of the barges carry rock aggregate, benzene, coal, and salt as part of the more than ninety million tons of cargo barged annually between St. Paul and St. Louis, but grain fills most of them. Of all the grain exported from the United States, 60 percent moves by barge down the river to terminals



7.5 *Above,* towboat and barges on the upper Mississippi. This is a relatively small collection of barges being pushed by a single towboat. *Below,* grain elevator along the upper Mississippi River. Grain is trucked from surrounding fields for storage in the large silos, then loaded directly onto river barges.

between Baton Rouge and New Orleans, where it is loaded for transport to Asia and other regions.

The Mississippi has been called a river of grain; fifty-five million tons are exported each year from the Mississippi drainage, in addition to what is consumed within the United States. The big river also reflects the flow of grain in more subtle ways. Water evaporated from oceans, forests, and lakes falls as precipitation over the drainage basin, creating the surface and subsurface moisture that nourishes the vast fields of corn, soybeans, and wheat. Nitrogen and phosphorus fertilizers and organochlorine pesticides manufactured across the United States are carried to the Upper Mississippi basin to fertilize the fields of the nation's breadbasket. Rainwater and snowmelt running off the farm fields carry along fertilizers and pesticides attached to the particles of sand, silt, and clay eroding from the fields. Eventually these particles of water, sediment, and attached contaminants make their way through surface and subsurface paths into tributary rivers and then the Mississippi itself.

These by-products of the national grain production industry join the downstream flow of the grain, but they do not move as efficiently or predictably as the grain barged along a channel that has been largely engineered for just this purpose. Some of the sediment accumulates in each navigation pool upstream from a lock and dam complex. Some of the sediment spreads across the floodplain wetlands and is stored there. Some of it moves all the way down the river to settle in the Mississippi's delta, or in the zone where river and ocean waters mix in the Gulf of Mexico. Attached contaminants move with the sediment all along this complex path with its shorter- and longer-term storage sites.

Other contaminants travel dissolved in the river water. Nitrogen intended to produce fields flush with cornstalks now feeds algae in the Gulf of Mexico, creating algal blooms that cover a swath as big as New Jersey. Concentrations of nitrate in the river and some of its tributaries have increased by two to five times since the early 1900s as farmers have applied more and more nitrogen fertilizers to their fields to increase yields. This overapplication means that much of the nitrogen simply runs off the field into surface water and groundwater. The flux of nitrate to the Gulf has tripled in the past thirty years, with most of the increase occurring between 1970 and 1983. Much of this nitrogen comes from the agricultural lands of the Upper Mississippi.

Pesticides such as atrazine, applied to corn in these agricultural lands, also move in solution into surface water and groundwater used for drinking. Pesticides are ubiquitous in the Upper Mississippi. An estimated two-thirds of all pesticides used nationally for agriculture are applied within the Mississippi River basin. The hazards to human and environmental health vary with the land use patterns along the river and with the resulting chemical brew that is present in different portions of the river.

A 1995 study of pesticides throughout the Mississippi River basin by U.S. Geological Survey scientists found atrazine and metolachlor in more than 95 percent of the samples, although maximum contaminant levels and health advisories recommended by the Environmental Protection Agency were exceeded in only a small percentage. In most conditions atrazine degrades rapidly to less toxic compounds (although it can persist for more than a year in dry, sandy soils and cool climates), but it is linked to breast and ovarian cancer in humans. Conservative estimates of mass transport indicate that the Mississippi discharges 176 tons of atrazine, 78 tons of cyanazine, 62 tons of metolachlor, and 20 tons of alachlor into the Gulf of Mexico each year. Scientists from the U.S. Geological Survey concluded that pollution by agrochemical runoff and groundwater may be the most significant recent factor responsible for deterioration of water quality in the big river and its tributaries.

Not only are these poisons present in the waters draining directly from agricultural lands, U.S. Geological Survey samples throughout the Mississippi drainage basin found *detectable levels of multiple pesticides in every rain and air sample collected from urban and agricultural sites.* Samples from a background site near Lake Superior in Michigan, removed from dense urban and agricultural areas, detected compounds including atrazine. These results indicate atrazine's propensity for long-range atmospheric transport.

One bargeload of grain represents 120 hectares of land devoted to agricultural production. It also represents an unmeasured flush of topsoil, fertilizers, and poisonous pesticides all along the river and into the biologically rich Gulf of Mexico.

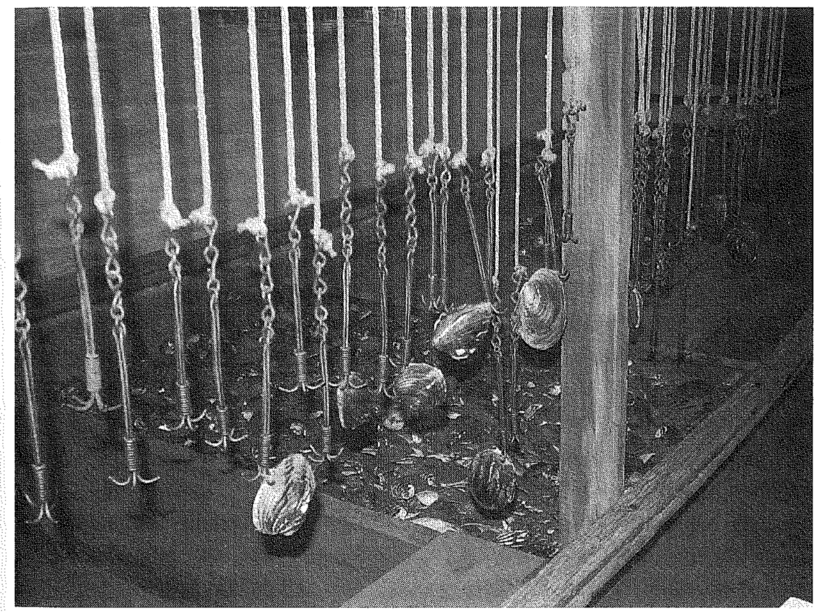
Mussels

Some of the sediment and nutrients moving down the Mississippi historically were filtered from the water by extensive beds of freshwater mussels, but this cleansing function has been seriously compromised by loss of mussels from overharvest. Native Americans harvested mussels living in the streams of the Mississippi River basin to obtain food

and freshwater pearls. As the encroaching Europeans pushed the Native Americans west of the Mississippi, the many species of mussels in the river system had a brief reprieve, and by the late nineteenth century they were abundant along many of the stream channels. The reprieve ended in 1891 when German immigrant John Boepple developed a way to use the mussel shells in manufacturing buttons and opened a small factory in Muscatine, Iowa.

Within a decade, mussel harvest and button manufacture formed an economic mainstay of towns all along the river. Working from north of Prairie du Chien, Wisconsin, to south of Canton, Missouri, the industrious mussel gatherers harvested twenty-four thousand tons of mussel shells in 1899 alone. This level of harvest could not be sustained, particularly because mussel gatherers customarily collected every mussel they could find.

The invention of the "crowfoot" in the late 1890s accelerated the mussel harvest. The crowfoot consisted of numerous four-pronged hooks attached to an iron bar. Mussels rest on the streambed with their shells



7.6 The crowfoot used to harvest mussels, here in an exhibit at the National Mississippi River Museum and Aquarium in Dubuque, Iowa. Widespread use of this harvesting technique severely disrupted mussel communities and led to declines in their numbers.

partially open to filter water through their soft tissues. When the crowfoot was dragged along the streambed, the touch caused the mussels to snap their shells shut on the hooks, making it easy to lift them into a boat. Fishermen using a crowfoot harvested from deeper waters that might otherwise have served as a refuge to maintain breeding populations of mussels. Widespread use of the device led to repeated dragging and disruption of mussel beds, causing gravid females to abort and injuring very small mussels so seriously that they died even if returned to the water. By the 1930s, a combination of falling prices, increasing rarity of mussels, and habitat degradation from repeated dragging and from sedimentation and water pollution finally destroyed the pearl button industry.

The Upper Mississippi River basin today contains sixty-two species of mussels, which represent 20 percent of the three hundred species found within the United States and Canada. The U.S. Fish and Wildlife Service lists five species as endangered, and NatureServe considers sixteen species imperiled, or 26 percent of the Upper Mississippi mussel species. As in the case of fish, habitat loss and water pollution are among the problems contemporary mussel populations face. The introduced and prolific zebra mussel, which literally smothers native mussels by crowding on top of them, may pose the greatest threat. Zebra mussels rode the surging waters of the 1993 flood down the Illinois River into the Mississippi and are now spreading largely unchecked.

The 1993 Flood

A steep flight of concrete stairs rises from the river in St. Louis, Missouri, with an immense silvery arch standing beyond the stairs. This is Gateway Arch, symbol of a national gateway to the West. Here the Illinois and the Missouri rivers join the Mississippi. Much of the westward expansion of the United States followed the Missouri and its tributaries upstream to the Rocky Mountains. Above the steps rising from river level in St. Louis lie the high-water marks from the 1993 flood, which rose to less than a meter below the top of the flood wall. All along the upper river rise levees and flood walls built in response to the floods of 1965 and 1973, but it is the more recent 1993 flood that truly forms the upper basin's high-water mark.

The 1993 flood was the greatest ever recorded at forty-two of the stream gauging stations in the Upper Mississippi basin. The volumes of water pouring out of the Mississippi during August 1993 were so

great that the water could easily be traced as it moved southeast around Florida and then up the east coast to North Carolina in September. The flood inundated more than 2.7 million hectares of agricultural and urban lands, and estimates of economic damage range between twelve and sixteen billion dollars. After the flood, the Federal Emergency Management Agency "hazard mitigated" over twelve thousand properties through acquisition, relocation, elevating, or flood-proofing with levees or other structures. The government also purchased two thousand hectares of floodplain for the Big Muddy National Fish and Wildlife Refuge along the Missouri River. As economic costs increase with each major flood despite the levee system and other engineered structures, we will be able to reduce flood damage only by eventually moving as many people and structures as possible out of the historical floodplain.

As on the Danube, the Ob, the Nile, and the Ganges, floods spread out across the Mississippi's extensive bottomlands before people began to channelize the river and confine it within levees. The wetlands and riverine forests of the bottomlands slowed the downstream passage of floods, decreasing the highest discharge at any point along the river by attenuating the flood peak and allowing sediment suspended in the floodwaters to settle out in areas of lower velocity. Invertebrates, fish, and plants living along the Mississippi adapted to the flood pulses and came to rely on seasonal access to the habitat and nutrients provided by floods. Nutrients and organic matter released from newly flooded soils, for example, stimulate microbial activity and the production of creatures that serve as fish food just at the time that fish larvae need to feed on such minute organisms. The small fish can also escape predatory larger fish in the shallow waters of the floodplain. As the Mississippi was progressively confined between levees during the nineteenth and twentieth centuries, the floodplains were converted to agriculture or other land uses, and the floods were contained within the leveed main channel. Levees are built primarily to limit inundation during floods, but their effect has become very controversial in many cases.

Those behind the levees are safe as long as the levees remain intact and continuous. But by conveying water more rapidly downstream, levees can enhance the flood peak dumped onto downstream areas unprotected by levees. And if the levees fail, the site of failure becomes like a firehose that effectively directs rapidly moving water and sediment onto the former floodplain. The intact portions of the levee then keep water from moving back into the channel as the flood recedes.

Levees can fail by being overtopped, by becoming saturated and collapsing through liquefaction, by slumping, or by being undermined. Levee failures during the 1993 flood created sites of rapid flow and intense turbulence that scoured the floodplain and channeled sediment into areas far from the main river channel. Up to 28 percent of the total Mississippi discharge flowed through one large levee break complex at Miller City, Illinois, carrying with it nearly 8.5 million cubic meters of sand.

The floodwaters spreading across the Mississippi bottomlands during 1993 benefited some organisms. Populations of native fish grew after the 1993 flood, reflecting increased production of juvenile fish on newly accessible floodplain habitats. Thirty-six species used the floodplain for spawning and nursery areas along the lower Illinois River. As the floodwaters gradually receded, some of the new fish went to feed predatory fish and birds, which also increased after the flood.

The ecological downside of the 1993 flood was twofold: the spread of pest species and of contaminants. Mosquitoes and introduced zebra mussels thrived during the inundation. Zebra mussels were accidentally introduced to the Great Lakes in the ballast water of ships coming from Europe. The prolific, highly mobile larvae of these mussels followed the canal system of Chicago from Lake Michigan to the Illinois River, and the 1993 floodwaters transported huge numbers downstream into the Mississippi.

Agricultural, urban, and industrial contaminants were also dispersed on an unprecedented scale during the 1993 flood. The Mississippi River basin contains the largest and most intensive agricultural region in the United States. More than 80 percent of the corn and soybeans grown in the country, and much of the cotton, rice, sorghum, and wheat, comes from the basin. To increase yields from these crops, more than 110,000 tons of pesticides and about 6.3 million tons of nitrogen fertilizer were applied to the basin in the early 1990s. Runoff pouring from farm fields through the Upper Mississippi basin in 1993 carried a witch's brew of poisons. Despite the much greater volume of water flowing down the rivers, concentrations of nitrate and herbicides were similar to the highest concentrations measured during the much lower flows of spring and summer 1991 and 1992. In other words, the dilution often seen during floods failed to take place in 1993. The 1993 flood flushed an estimated half a million kilograms of atrazine and 911,800 tons of nitrate nitrogen into the Gulf of Mexico.

Water discharging from the Mississippi River plays a critical role in the ecosystem of the Gulf. Discharge from the Mississippi and Atchafalaya rivers forms the Louisiana Coastal Current, and biological productivity in the Gulf is highest along this river plume because of the nutrients carried into the ocean with the river water. Nitrogen is the nutrient that most commonly limits the productivity of estuarine and coastal waters. But excess nutrients can definitely be too much of a good thing.

Increasing amounts of nitrogen have been flushed downstream to the Gulf as the application of nitrogen fertilizers has become more widespread in the Mississippi drainage basin. Here the nitrogen stimulates algal blooms along the Louisiana coast. As in the Lake Victoria algal blooms indirectly caused by Nile perch, when the masses of algae in the Gulf of Mexico caused by excess nitrogen from the Mississippi River die and sink, the decaying organic matter uses up oxygen in the bottom layer of the water, creating anoxic conditions in which other organisms cannot survive. Nitrogen loading was recognized as a growing problem before 1993, when so-called dead zones of eight thousand to eleven thousand square kilometers formed in the Gulf each year. During 1993 the dead zone grew to nearly seventeen thousand square kilometers, and this greater extent persisted in 1994. The dead zone has continued to fluctuate between thirteen thousand and twenty thousand square kilometers, with no sign of decreasing.

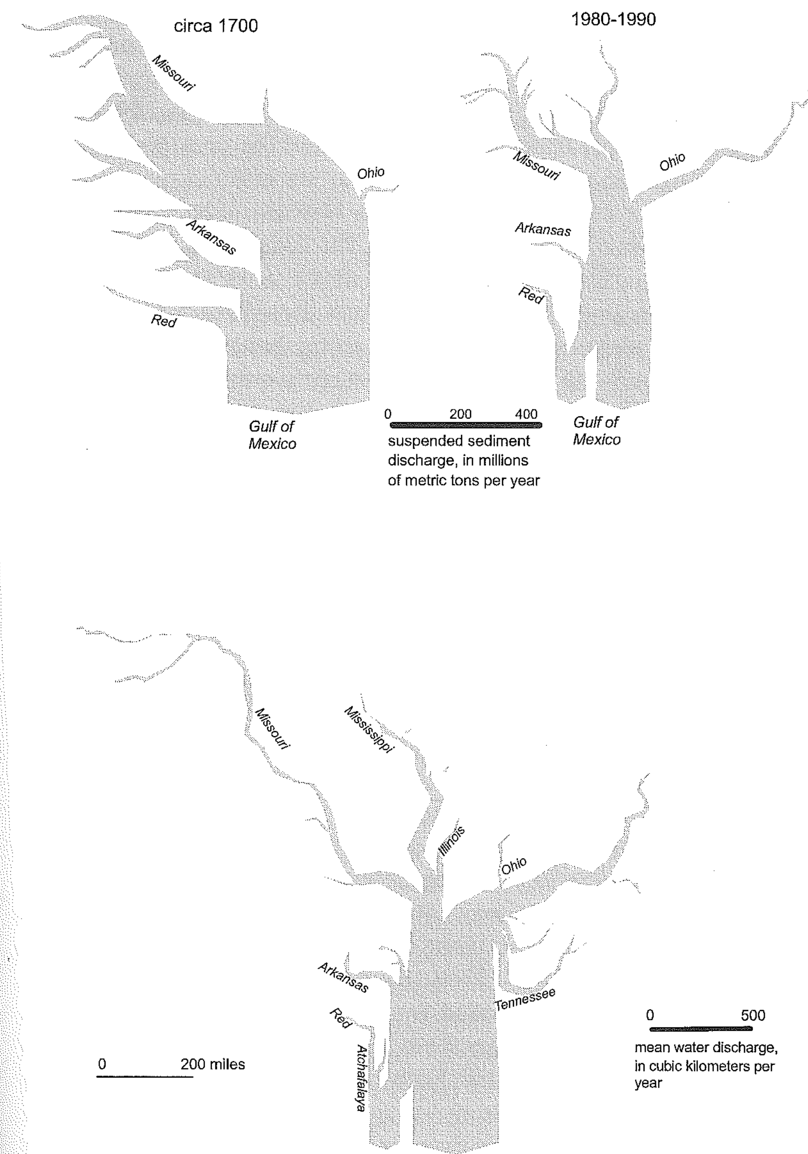
The only effective way to limit the flush of nitrogen into the Gulf, and thus the existence of the dead zone, is to reduce nitrogen loss at the source; the farm fields of the Mississippi River basin. Suggestions include reinventing the agricultural system of the Corn Belt. The current system features low economic returns and high nutrient and sediment losses, but it could be altered to create a more ecologically based landscape emphasizing nutrient sinks and a legume base for supplementing fertilizer nitrogen (something more like the corn-beans-squash crop rotation of the Native Americans that relied on nitrogen-producing legumes to fertilize the soil). Natural and created wetlands and riverside belts of vegetation also buffer rivers by absorbing excess nitrogen coming from farm fields and urban wastewater treatment plants. Allowing Mississippi River water to spread across the floodplain of the river's delta would result in some nitrogen uptake and storage by deltaic wetland plants. The combination of changed farm practices and riverside, wetland, and delta buffer zones has the potential to substantially reduce nitrogen inputs to the Mississippi River. This would improve water quality all along the river and allow the ecologically and commercially important Gulf fisheries to recuperate.

CHAPTER SEVEN

The Illinois and the Missouri

The Illinois and Missouri rivers, two of the Mississippi's primary tributaries, enter the main river within a few kilometers of each other. Each river basin reflects, on a smaller scale, many of the environmental changes present on the Mississippi. The Illinois River joins the Mississippi from the east near St. Louis. The river drains 80,300 square kilometers, most of them in the state of the same name. The river basin parallels the Upper Mississippi River basin as a whole in that historically extensive floodplain forests and wetlands that supported abundant fish, waterfowl, and other organisms were systematically converted to farmlands during the nineteenth and twentieth centuries. Levee construction, land drainage, agricultural and urban pollutants, and channelization, along with increasing sediment loads from upland farming, altered the riverine corridor and caused substantial declines in the abundance and diversity of the river's plant and animal communities. Despite these massive losses and accumulating problems, a 1992 National Research Council report identified the Illinois River as one of the country's few large floodplain river systems that still retain enough natural characteristics to allow for restoration. The Nature Conservancy, the Illinois Department of Natural Resources, and other private and government groups are acquiring forests and wetlands along the river, restoring a functioning ecosystem hectare by hectare.

The Missouri River enters from the west a few kilometers downstream from the junction of the Mississippi and Illinois rivers. Of all the Mississippi's tributaries, the Missouri carries the greatest load of sediment because it crosses sedimentary rocks that weather and release abundant sediment in the semiarid climate that characterizes much of the Missouri's drainage, as well as erodible glacial deposits on the Great Plains. The loads of sediment carried in suspension by the Mississippi have decreased by half since the Mississippi valley was first settled by Europeans. This decrease has occurred mainly since 1950, because the numerous large reservoirs built in the Missouri River drainage now effectively trap about 80 percent of the sediment coming downstream. The Missouri, however, still contributes more than half the Mississippi's total sediment load. This load is not matched by the Missouri's water flow. Because of the great dry swath created by the rain shadow of the Rockies, the 3,860 kilometer Missouri drains 43 percent of the Mississippi's total area but contributes only 12 percent of the Mississippi's total discharge.



7.7 Schematic illustration of historical and contemporary contributions to suspended-sediment discharge (*above*) and water discharge (*below*) of the Mississippi River. (After Meade 1996, figures 5 and 6.)

As on the Mississippi, channel alterations accompanied nineteenth-century steamboat traffic on the Missouri. A history of frequent flooding also led to piecemeal construction of urban levees and encouraged the Corps of Engineers to build the first dam on the mainstem Missouri in 1938 at Fort Peck, Montana, although the dam is principally used for navigation and hydropower. Today six major dams, from Fort Peck downstream to Gavins Point, on the Nebraska–South Dakota border, regulate flows on the main channel. The course of the Missouri between these dams has been transformed into a series of lakes separated by short river segments, whereas the river downstream from Gavins Point has been altered more by straightening, bank stabilization, and levee construction—all the changes necessary to create a 2.7 meter deep navigation channel 1,225 kilometers long. Approximately 10 percent of the original floodplain is now inundated during the average annual flood because levees confine the lower Missouri River to a width of 180 to 330 meters. The river engineering favored the growth of farming in the river's former floodplain, as well as a network of barge traffic. Nearly 95 percent of the Missouri River basin's landmass is devoted to agriculture, and farmers, along with barge operators, are now vocal opponents of scientists and environmentalists who seek to change river management along the Missouri.

Environmentalists question whether the barge traffic, which peaked in 1977 and has been declining ever since, is worth the loss of much of the Missouri River ecosystem. Fisheries scientists attribute an 80 percent decline in the commercial fish harvest during the past century to river engineering. Sixteen fish species are listed as imperiled. Natural riparian vegetation has been nearly eliminated.

Localized restoration projects that attempt to halt or reverse this trend of species loss include controlled flooding on small parcels of intensively managed public lands along the lower Missouri River. Although these artificially flooded wetlands provide bird habitat, they remain disconnected from the main river by levees, at least in part to restrict wetland access by carp. Native, floodplain-dependent fish are also excluded from the wetlands. As on the mainstem Mississippi and the Danube, these restoration projects do not seek to re-create a fully functioning river ecosystem but rather aim to provide conditions that will benefit specific species or groups of species. Management of these isolated floodplain parcels reflects the "string of beads" restoration concept, in which not all of the river's floodplain needs to be reopened in order to revitalize the ecosystem. Instead, river health can be improved by acquiring key floodplain habitats such as flood-prone areas

near tributary confluences or remnant backwaters that form "beads" along the river corridor. Acquiring and managing individual beads is much more economically and politically feasible than attempting to restore the entire river corridor, and it can build public support with demonstrated benefits.

The Middle Mississippi

Along the middle segment of its course, the Mississippi flows 313 kilometers from the mouth of the Missouri to the mouth of the Ohio, the source of nearly half the Mississippi's water. For the first 170 kilometers the Mississippi flows in a trench five to seven kilometers wide eroded more than a hundred meters into Paleozoic bedrock. Limestone bluffs form valley walls well back from the main channel. Secondary channels, islands, sandbars, and a few abandoned channels continue to create complexity along the river's course, but the engineering present in the Upper Mississippi seems almost gentle compared with the increasingly restrictive system of levees the river encounters downstream. The Middle Mississippi is extensively diked to maintain the 2.7 meter navigation channel, and flood control levees narrow the extent of high water. By 1968, the surface area of the Middle Mississippi was 39 percent less than the area measured in 1888, before much of the channel engineering.

The Mississippi does not meander broadly until it passes through the Thebes Gap area of Missouri and Illinois, a gorge cut through Shawneetown Ridge by higher river flows about nine thousand years ago. Downstream from the gap the floodplain widens abruptly to nearly eighty kilometers, and the river's course grows more sinuous. From Thebes Gap downstream the river flows on the Mississippi Embayment, a deep trough of downward-folded bedrock filled with sediments deposited over the past few million years. As the Mississippi has meandered back and forth across its floodplain during thousands of years, it has created a complex, subtle topography of undulating low ridges and swales that represent former natural levee ridges and abandoned channels filled with ponded water or sediments. Crescent-shaped oxbow lakes lie among expansive, largely flat backswamps. On aerial photographs the lakes, ridges, and swales give the landscape a texture or grain, as though the surface is alive and growing.

Cairo, Illinois, sits at the junction of the Ohio River and the Mississippi, 288 river kilometers south of St. Louis. The name Ohio comes from Iroquois and means beautiful river. The French called the Ohio *la belle rivière*. The Ohio River and its tributaries drain 567,000 square kilometers, only one-sixth of the total area drained by the Mississippi, but contribute nearly half of the water discharged to the Gulf of Mexico. The Ohio contributed very little of the Mississippi's sediment load before European settlement, but the load increased by five to ten times as Europeans brought deforestation and row-crop farming to the drainage basin. As sediment clouded the water and accumulated along the channels, construction of a progressively deeper navigation channel mirrored the history of river engineering on the Mississippi. A 2.7 meter channel completed in 1929 now extends the full 1,635 kilometers from Pittsburgh to the Ohio's mouth and along 2,170 kilometers of tributaries. As on the Illinois River, the history of land use, river engineering, and loss of habitat and species along the Ohio mirrors that along the Mississippi.

The Lower Mississippi

Downstream from Cairo, Illinois, the river becomes officially the Lower Mississippi for the final 1,590 kilometers of its journey to the Gulf of Mexico. Almost everything beyond the main channel is hidden by levees in this flat landscape, and the riverscape is dominated by the constant barge traffic. In its lower reaches the Mississippi more than ever looks like an industrial river.

The natural floodplain beyond the levees includes nearly ninety-two thousand square kilometers and varies in width from thirty to two hundred kilometers. The Lower Mississippi was historically a very sinuous river, with a complex topography of abandoned channel remnants forming wetlands across the broad floodplain. Natural floodways formed by channels running roughly parallel to the Mississippi for some distance carried excess water during high floods. Flow into these channels is now mostly blocked by an extensive network of levees that has restricted the active floodplain to about ten thousand square kilometers. Today the Lower Mississippi is fairly straight, particularly along its lowermost portions from Baton Rouge, Louisiana, to the Gulf.

The levee system of the Lower Mississippi grew in fits and starts, much like the locks and dams on the upper river. French settlers at New Orleans began to construct levees to protect the city from floodwaters in 1717. In 1850 the Corps of Engineers began a survey of the Lower Mississippi that considered levees, natural and man-made outlets from the river, and cutoffs between river meanders as means of flood control. Another massive flood in 1858 hastened the Corps's study, which resulted in an 1861 report recommending a "levee-only" policy of flood control.

Predictably, the floods continued to come. Severe floods in 1903 and 1907 were followed by floods in 1912 and 1913 that destroyed many of the nonfederal levees and caused many deaths. This led to further pressure for government intervention in flood control. In 1917 Congress passed a Flood Control Act that called for further levee building. In his book *Rising Tide*, John Barry provides a fascinating account of the struggle between civilian and Army engineers to develop a flood-control policy for the Lower Mississippi. The Army's emphasis on levees won the day. Belief in the levee-only approach was reinforced when a near-historic flood in 1922 was contained by federally designed levees. In a classic example of hubris, the commanding general of the Corps of Engineers announced in 1927 that the Lower Mississippi levee system was ready to withstand the worst of floods. Two months later, the greatest flood yet on the Lower Mississippi overwhelmed the levees and spread over a hundred kilometer swath from Memphis southward to the Gulf. That was the end of the levee-only policy.

Like the 1993 flood on the upper river, the 1927 flood was preceded by months of rain. The coup de grâce was heavy rain over several hundred thousand square kilometers stretching from Illinois to Missouri and Texas. The 1993 flood on the upper river crested at 28,100 cubic meters per second in St. Louis. The 1927 flood crested at an estimated 84,270 cubic meters per second in New Orleans.

After 1927, flood control in the lower valley became completely a federal responsibility. Emphasis shifted from levees-only to recognition that other structures such as spillways and dams were also needed. The Corps built seventy-six reservoirs in the Upper Mississippi valley and forty-nine on the Missouri River and its tributaries. The Bureau of Reclamation added another twenty-two flood-control reservoirs on the Missouri. A nonstructural approach emphasizing reduced use of floodplain lands grew steadily more popular starting in the 1970s, but the floods continued to come and the levees continued to be built. At present, the channels of the Lower Mississippi drainage basin flow between 3,532 kilometers of levees.

This enormous riverine straitjacket created multiple changes in the Lower Mississippi. Major natural floodways were eliminated. The land area of the regularly flooded bottomlands was reduced by more than 90 percent. The remaining bottomlands are highly fragmented and have lost much of their ecological function. Floodplain lakes are isolated. Lateral channel migration, which historically created backwaters in the form of abandoned channels, largely ceased, causing deterioration of the diverse habitat necessary to support a wide variety of riverside vegetation, fish, birds, and other organisms.

The highest densities of larval fish along the Lower Mississippi are found in backwaters, which also serve as nurseries for juvenile fish. Rivers like the Ohio have large backwater areas where tributaries enter, but the Lower Mississippi has few tributaries. As existing backwaters along the lower river gradually fill with sediment, habitat for many river and floodplain organisms becomes progressively more limited.

Water surface elevation of the channel rose as flows along the lower river became progressively more confined between levees. Engineers severed fifteen meander bends between 1933 and 1942 to create a straighter channel with swifter flow to reduce water surface elevation. These artificial cutoffs shortened the river by 228 kilometers and did indeed create swifter flow--so swift that erosion was accelerated and the channel had to be stabilized with 1,368 kilometers of rock and other hard materials. River energy that would previously have gone into natural meander cutoffs and bend enlargement now goes into attempts to build midchannel bars, so that the Corps is kept busy dredging the main channel and removing the bars. A naturally functioning river is self-maintaining. Once you start engineering a river, you inevitably take on a constant maintenance project.

With continuing help from engineers, the channelized river flushes sediments and dissolved contaminants fairly efficiently into the Gulf of Mexico. Like the Twin Cities and St. Louis, Baton Rouge and New Orleans contribute high levels of urban contaminants to the Mississippi because of increased population densities. Industrial contaminants such as hexachlorobenzene enter the river from the industrial corridor along the lowermost four hundred kilometers of the Mississippi. This reach of the river is sometimes called cancer alley because the death rate from cancer and other diseases here is above the national average. As with contaminants in humans living along portions of the Ob and the Ganges, these statistics unfortunately are not difficult to understand given the context of toxic waste production. At least 136 major industries line the banks of the river along the 250 kilometers between Baton Rouge and New Orleans, mostly petrochemical plants that manufacture pesticides and plastics or refine oil. In 1987 these industries discharged eighty-nine million kilograms of toxic chemicals directly into the Mississippi.

The Mississippi passes New Orleans flowing at a higher level than the city. The steamboats so important to history along the rest of the river were first introduced here in 1812, and the region's economy continues to rely on commercial navigation. South of New Orleans the river has such uniform width and controlled bends that it looks artificial. The flat, wide river continues on through the Bayou, named from the Choctaw word *bayuk*, "creek," to its delta.

"Delta" can have different meanings in relation to the Mississippi. The word is used to describe the culture of a broad region that extends along the river from Vicksburg to Memphis. It is also used for the huge depositional zone the river occupied over the past few millennia and the relatively small zone where active deposition occurs today. During the past seven thousand years the active delta of the Mississippi has swung back and forth across a swath of coast nearly 420 kilometers wide. The river historically deposited so much sediment at its meeting point with the ocean that each lobe of the delta built up above the surrounding coastal wetlands. At some point during this process, the Mississippi would rapidly shift to an adjacent lower elevation and begin depositing another delta lobe. The contemporary delta, which projects into the Gulf like the long, skinny leg and foot of a bird, has now been active for about a thousand years.

Left to its own devices, the Mississippi would probably have shifted course sometime between 1965 and 1975 and begun flowing down the Atchafalaya River to create a new delta sublobe. The Atchafalaya, which drains forty-seven hundred square kilometers of land adjacent to the Mississippi River, became a distributary channel of the Lower Mississippi about four hundred years ago when a looping meander of the Mississippi intercepted both the Red and Atchafalaya river courses. Wood and sediment formed a plug at the entrance to the Atchafalaya that prevented it from capturing the flow of the Mississippi, despite the Atchafalaya's steeper downstream slope. In 1831 Henry Shreve created a cutoff on the Mississippi, intending to increase river velocity enough to eliminate siltation at the mouth of the Red River, which entered the Mississippi immediately upstream from the Atchafalaya. The cutoff meander became known as the Old River. Cutting off the big bend reduced water and logs entering the Atchafalaya, allowing private citizens and the State of Louisiana to begin dismantling the logjams over the next three decades. But clearing the logjams caused the Old River meander loop to become a new connection between the Atchafalaya and the Lower Mississippi.

The Atchafalaya has a three-to-one advantage in slope over the Lower Mississippi. As more and swifter water flowed down the new pathway, the Atchafalaya was well on its way to becoming the Mississippi until the Corps stepped in. In *Designing the Bayous*, Martin Reuss describes in detail the long history of river engineering as the Corps attempted to prevent the Atchafalaya from capturing the Mississippi's flow. The Corps interfered with the process of river capture because the infrastructure of coastal and lower river navigation existing along the Mississippi by that time could not be replicated along the new channel without enormous expense. Internationally respected engineers including Hans Einstein, Albert Einstein's son, worked with the Corps for years to design the low dam that now controls flow into the Atchafalaya. The Old River Control Structure is a concrete sill within the main channel that extends more than a kilometer onto the adjacent overbank areas. The structure was completed in October 1963, but problems with its integrity and function began in 1964 and continue to the present. The Corps is fighting a battle that the river will eventually win. Meanwhile, navigation interests, farmers, and environmentalists seeking to preserve the Atchafalaya's wetlands argue over river engineering and flow regulation in this region where wetlands are becoming scarcer and scarcer.

The Atchafalaya wetlands adjoin a much larger, discontinuous wetlands complex that spreads along the margins of the Gulf of Mexico. The Mississippi River delta alone has seven hundred thousand hectares of coastal marsh. This is the largest continuous wetland in the nation and constitutes part of one of the world's largest estuarine areas. The region is also exceptionally rich ecologically. The marshes and bayous shelter eleven threatened and endangered species and provide winter habitat for fifteen million waterbirds.

The problem with this region for which superlatives of size and richness so readily come to mind is that it is also disappearing at a rate easily described with superlatives. Louisiana has been losing coastal wetlands faster and faster throughout the twentieth century. Estimates of average loss rise from 17 square kilometers a year in 1913 to 117 square kilometers a year during the 1960s, before declining to 69 at present. That last figure might not sound so bad by comparison, but it translates to 0.8 hectare of wetlands lost every hour, part of a cumulative loss estimated at 3,900 to 5,300 square kilometers since the 1930s.

It is not difficult to find potential explanations for this hemorrhaging of wetlands. First, the barrier islands that provide the first line of defense against the erosive power of hurricanes and tropical storms are themselves eroding. Oil and gas pipelines and access canals affect the islands' stability, and pollution of many types reduces the ability

of coastal vegetation to stabilize them. Jetties and seawalls intercept sediment moving along the coast by longshore transport (just offshore parallel to the coast) that would normally replenish sediment removed from the barrier islands by wave erosion.

Second, sea level at the Mississippi delta is rising by 1.2 to 4.3 centimeters each year. About 20 percent of this rise is caused by melting of the world's remaining glaciers. The remaining 80 percent is actually relative as the coastal sediments subside through combined normal compaction of sediments and human removal of water, oil, and natural gas. The input of sediment to the delta also declined substantially during the twentieth century as upstream dams stored sediment along the Missouri and the Mississippi. Engineered bypasses of the Lower Mississippi River and closed distributary channels on the delta further direct the sediment that does reach the coast away from the delta and into the deep water beyond the continental shelf.

Third, most of the land loss is not from the periphery and shoreline erosion but from internal breakup of marsh vegetation as a result of physiological stresses. Levees built throughout the wetlands during the 1930s ended the spring floods that replenished local soils and water tables. The nutria (*Myocastor coypus*), a large rodent from South America, escaped from captivity and began devouring the roots of marsh plants that had not evolved to withstand such herbivory. The Corps built fourteen major ship channels to inland ports by the 1960s. Wind and water erosion along the channels magnify saltwater intrusion that kills the freshwater wetland plants. More than thirteen thousand kilometers of canals thread back and forth through the great wetlands complex, exacerbating erosion and saltwater intrusion. Natural gas and oil pipelines, and associated maintenance paths, also disrupt the wetlands and contribute to their degradation.

Despite the many recent changes in the flow of water, sediment, and nutrients, the Louisiana wetlands continue to support a commercial fishery worth three hundred million dollars annually. More than two million people live in and around the coastal wetlands, and they are very much aware of land loss. Coastal areas are eroding so rapidly that changes are readily perceived over a decade or two. Engineering responses to date include releasing freshwater to mimic spring floods. Engineers also divert freshwater into the delta to decrease salinity. They rebuild marshes with dredge material and salt-tolerant plants and attempt to increase the sediment released to the delta. Stabilizing the shoreline and restoring barrier islands can also help reduce coastal erosion.

Despite spending half a billion dollars in the past decade, none of these experiments has effectively counteracted the regional trend of land loss. At present the Corps and other groups have a fourteen billion dollar unfunded plan to save the rest of the coastal wetlands. The situation will not change unless the level of funding and the integration among individual components of the plan are comprehensive enough to address a problem that has been building for decades and that extends from the headwaters dams to the offshore drilling rigs. As on the Ob, the Danube, the Nile, and the Ganges, changes associated with land use and river engineering throughout the Mississippi's huge drainage basin combine to cause major problems in the river's delta and coastal zone.

Restoring the River

It is tempting to conclude this chapter by writing, "Thus the Mississippi ends, not with a bang but a whimper." This giant among rivers that once built a huge delta far into the Gulf of Mexico now recedes daily, its flow tapped and regulated, its sediment trapped all along the river's path and contaminated with chemicals that will have unpredictable effects for decades to come. This is a grim picture for the great national river, but it can be a snapshot along the way, not the final portrait.

The National Research Council identifies the Upper Mississippi as an ecological rarity, for its size, that still preserves enough floodplain and flood pulse to allow restoration. In 2004 the Nature Conservancy developed a list of forty-seven priority conservation areas within the Upper Mississippi. These segments of river can be revitalized by protecting undeveloped lands and restoring natural processes of flooding and channel movement. But time is running out as population and land use inexorably increase. This is why many of the scientists who study the Mississippi River system and the citizens who live along it feel a sense of urgency in protecting and restoring the river.

The Mississippi is not exceptionally polluted compared with major rivers in other industrialized countries. Sources of pollution have been and can continue to be reduced. Polluted sediments can be remediated. Towns and cities throughout the drainage substantially improved sewage treatment, for example, after the Clean Water acts of the late 1960s and early 1970s. Oil slicks are now rarely seen on the river, despite in-stream refueling of barges, because the Coast Guard monitors in-stream polluters and enforces regulations. Phosphate pollution and the

attendant sudsy patches floating on the rivers have decreased following changes in detergent chemistry in the early 1990s.

Dams and other engineering infrastructure can be removed or operated in ways less disruptive of natural flow cycles. Although most dams operated for navigation along the Upper Mississippi are unlikely to be removed, the partnerships established between the Corps of Engineers, the Nature Conservancy, and other government agencies and environmental organizations point the way toward balancing commercial and environmental needs along the Mississippi.

Damaging floods can also provide opportunities to restore natural landscapes in the floodplain. Approximately eighty-one hundred hectares along the Lower Missouri are now in public ownership as a result of buyouts since the 1993 flood. Waterfowl use the river's side channels, and cottonwood and willow forests are regenerating in the resulting Big Muddy National Wildlife Refuge.

The restoration of floodplain wetlands and the reconnection of the main river and secondary channels is not an all-or-nothing proposition. Acquiring and managing critical "beads" along the rivers can create the strings of restored habitat that will serve as lifelines to many plant and animal species and to the health of the river ecosystem as a whole. This concept is particularly amenable to a gradual approach and localized actions that can help give residents of the river corridor a sense of stewardship and that can be effectively pursued by nongovernmental organizations working in concert with government agencies.

The Mississippi River and the surrounding landscape are still present, still vital, and still capable of being restored. The Mississippi, as described in the title of a 2000 publication, is a working river and a river that works (Upper Mississippi River Conservation Committee 2000). Like the countries along the Danube, the United States has the technical knowledge and the monetary resources to restore the river corridor. If we choose, we can once more connect our greatest national river, from its headwaters to the ocean, with the adjacent floodplains and uplands that keep the river corridor vital.

Schneider, E. 2002. The ecological functions of the Danubian floodplains and their restoration with special regard to the Lower Danube. *Archives of Hydrobiology Supplement* 141:129–49.

Tamas, S., N. Nicolescu, T. Toader, and F. Corduneanu. 2001. Floodplain forests of the Danube delta. In *The floodplain forests in Europe: Current situation and perspectives*, ed. E. Klimo and H. Hager, 221–32. Leiden: Brill.

Tockner, K., C. Baumgartner, F. Schiemer, and J. V. Ward. 2000. Biodiversity of a Danubian floodplain: Structural, functional and compositional aspects. In *Biodiversity in wetlands: Assessment, function and conservation*, ed. B. Gopal, W. J. Junk, and J. A. Davis, 1:141–59. Leiden: Backhuys.

Interlude

Daskalov, G. M. 2003. Long-term changes in fish abundance and environmental indices in the Black Sea. *Marine Ecology Progress Series* 255:259–70.

Kideys, A. E. 2002. Fall and rise of the Black Sea ecosystem. *Science* 297:1482–84.

Meinesz, A. 2001. *Killer algae: The true tale of a biological invasion.* Chicago: University of Chicago Press.

Chapter Six. The Ganges: Eternally Pure?

Adel, M. M. 2002. Man-made climatic changes in the Ganges basin. *International Journal of Climatology* 22:993–1016.

Agnihotri, N. P., V. T. Gajbhiye, M. Kumar, and S. P. Mohapatra. 1994. Organochlorine insecticide residues in Ganges River water near Farrukhabad, India. *Environmental Monitoring and Assessment* 30:105–12.

Ahmad, S., M. Ajmal, and A. A. Nomani. 1996. Organochlorines and polycyclic aromatic hydrocarbons in the sediments of Ganges River (India). *Bulletin of Environmental Contamination and Toxicology* 57:794–802.

Alley, K. D. 2002. *On the banks of the Ganga: When wastewater meets a sacred river.* Ann Arbor: University of Michigan Press.

Bandyopadhyay, J. 2002. Water management in the Ganges-Brahmaputra basin: Emerging challenges for the 21st century. In *Conflict management of water resources*, ed. M. Chatterji, S. Arlosoroff, and G. Guha, 179–218. Hampshire, UK: Ashgate.

Biswas, Asit K., and Juha I. Uitto, eds. 2001. *Sustainable development of the Ganges-Brahmaputra-Meghna basins.* Tokyo: United Nations University Press.

Chander, D. V. R., C. Venkobachar, and B. C. Raymahashay. 1994. Retention of fly ash-derived copper in sediments of the Pandu River near Kanpur, India. *Environmental Geology* 24:133–39.

Ives, J., and D. C. Pitt, eds. 1988. *Deforestation: Social dynamics in watersheds and mountain ecosystems.* London: Routledge.

Kannan, K., R. K. Sinha, S. Tanabe, H. Ichihashi, and R. Tatsukawa. 1993. Heavy metals and organochlorine residues in Ganges River dolphins from India. *Marine Pollution Bulletin* 26:159–62.

Kumar, K. S., K. Kannan, O. N. Paramasivan, V. P. S. Sundaram, J. Nakanishi, and S. Masunaga. 2001. Polychlorinated dibenzo-p-dioxins, dibenzofurans, and polychlorinated biphenyls in human tissues, meat, fish, and wildlife samples from India. *Environmental Science and Technology* 35:3448–55.

Markandya, A., and M. N. Murty. 2004. Cost-benefit analysis of cleaning the Ganges: Some emerging environmental and development issues. *Environment and Development Economics* 9:61–81.

Mirza, M. M. Q., ed. 2004. *The Ganges water diversion: Environmental effects and implications.* Dordrecht: Kluwer.

Morrison, P., and P. Morrison. 2002. No one checked: Natural arsenic in wells. *American Scientist* 90:123–25.

Rahman, M. M., M. Q. Hassan, M. S. Islam, and S. Z. K. M. Shamsad. 2000. Environmental impact assessment on water quality deterioration caused by the decreased Ganges outflow and saline water intrusion in south-western Bangladesh. *Environmental Geology* 40:31–40.

Sainju, M. M. 2002. Some issues related to conflict management of water resources in Nepal. In *Conflict management of water resources*, ed. M. Chatterji, S. Arlosoroff, and G. Guha, 251–58. Hampshire, UK: Ashgate.

Sarkar, S. K., A. Bhattacharya, and B. Bhattacharya. 2003. The river Ganga of northern India: An appraisal of its geomorphic and ecological changes. *Water Science and Technology* 48:121–28.

Sharma, C. B., and N. C. Ghose. 1987. Pollution of the river Ganga by municipal waste: A case study from Patna. *Journal of the Geological Society of India* 30:369–85.

Siddiqi, N. A. 1997. *Management of resources in the Sundarbans mangroves of Bangladesh.* Intercoast Network, Mangrove edition, Coastal Resources Center. Narragansett Bay: University of Rhode Island.

Singh, M. 2001. Heavy metal pollution in freshly deposited sediments of the Yamuna River (the Ganges River tributary): A case study from Delhi and Agra urban centres, India. *Environmental Geology* 40:664–71.

Smith, B. D., B. Bhandari, and K. Sapkota. 1996. *Aquatic biodiversity in the Karnali and Narayani river basins–Nepal.* Kathmandu: IUCN–World Conservation Union.

Subramanian, V., N. Madhavan, R. Saxena, and L. C. Lundin. 2003. Nature of distribution of mercury in the sediments of the river Yamuna (tributary of the Ganges), India. *Journal of Environmental Monitoring* 5:427–34.

Chapter Seven. The Mississippi: Once and Future River

Balogh, S. J., D. R. Engstrom, J. E. Almendinger, M. L. Meyer, and D. K. Johnson. 1999. History of mercury loading in the Upper Mississippi River reconstructed from the sediments of Lake Pepin. *Environmental Science and Technology* 33:3297–3302.

Barry, J. M. 1997. *Rising tide: The great Mississippi flood of 1927 and how it changed America*. New York: Simon and Schuster.

Brown, A. V., K. B. Brown, D. C. Jackson, and W. K. Pierson. 2005. Lower Mississippi River and its tributaries. In *Rivers of North America*, ed. Arthur C. Benke and Colbert E. Cushing, 231–81. Amsterdam: Elsevier.

Changnon, S. A., ed. 1996. *The great flood of 1993: Causes, impacts, and responses*. Boulder, CO: Westview.

Changnon, S. A. 1998. The historical struggle with floods on the Mississippi River basin. *Water International* 23:263–71.

Clay, F. M. 1983. *History of navigation on the lower Mississippi*. U.S. Army Engineer Water Resources Support Center, Navigation History NWS–83-8. Washington, DC: U.S. Government Printing Office.

Costner, P., and J. Thornton. 1989. *We all live downstream: The Mississippi River and the national toxics crisis*. Seattle: Greenpeace, Vision Press.

Delong, M. M. 2005. Upper Mississippi River basin. In *Rivers of North America*, ed. A. C. Benke and C. E. Cushing, 327–73. Amsterdam: Elsevier.

Dickens, C. 1842 (1972). *American notes for general circulation*. Harmondsworth, UK: Penguin Books.

Fremling, C. R. 2005. *Immortal river: The Upper Mississippi in ancient and modern times*. Madison: University of Wisconsin Press.

Fremling, C. R., J. L. Rasmussen, R. E. Sparks, S. P. Cobb, C. F. Bryan, and T. O. Claflin. 1989. Mississippi River fisheries: A case history. In *Proceedings of the International Large River Symposium*, ed. D. P. Dodge. Canadian Special Publication of Fisheries and Aquatic Sciences 106, Ottawa: Department of Fisheries and Oceans.

Goldstein, R. M., K. Lee, P. Talmage, J. C. Stauffer, and J. P. Anderson. 1999. *Relation of fish community composition to environmental factors and land use in part of the Upper Mississippi River basin, 1995–97*. U.S. Geological Survey Water-Resources Investigations Report 99–4034. Washington, DC: U.S. Geological Survey.

Goolsby, D. A., W. A. Battaglin, G. B. Lawrence, R. S. Artz, B. T. Aulenbach, R. P. Hooper, D. R. Keeney, and G. J. Stensland. 1999. *Flux and sources of nutrients in the Mississippi-Atchafalaya River basin*. Topic 3 report on the integrated assessment on hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series 17. Silver Spring, MD: NOAA Coastal Ocean Program.

Hoops, R. 1993. *A river of grain: The evolution of commercial navigation on the Upper Mississippi River*. College of Agricultural and Life Sciences Report R3584. Madison: University of Wisconsin.

Keeney, D. R. 2002. Reducing nonpoint nitrogen to acceptable levels with emphasis on the Upper Mississippi River basin. *Estuaries* 25:862–68.

Kesel, R. H. 2003. Human modifications to the sediment regime of the Lower Mississippi River floodplain. *Geomorphology* 56:325–44.

Manning, R. 2004. *Against the grain: How agriculture has hijacked civilization*. New York: North Point Press. McCall, E. 1984. *Conquering the rivers: Henry Miller Shreve and the navigation of America's inland waterways*. Baton Rouge: Louisiana State University Press.

Meade, R. H., ed. 1996. *Contaminants in the Mississippi River, 1987–92*. Circular 1133. Washington, DC: U.S. Geological Survey.

Meade, R. H., T. R. Yuzyk, and T. J. Day. 1990. Movement and storage of sediment in rivers of the United States and Canada. In *Surface water hydrology*, ed. M. G. Wolman and H. C. Riggs, 255–80. Boulder, CO: Geological Society of America.

Merritt, R. H. 1984. *The Corps, the environment, and the Upper Mississippi river basin*. Washington, DC: Office of the Chief of Engineers, U.S. Government Printing Office.

Mitsch, W. J., J. W. Day, J. W. Gilliam, P. M. Groffman, D. L. Hey, G. W. Randall, and N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River basin: Strategies to counter a persistent ecological problem. *BioScience* 51:373–88.

Pike, Z. M. 1810. *An account of expeditions to the sources of the Mississippi, and through the western parts of Louisiana, to the sources of the Arkansaw, Kans, La Platte, and Pierre Jaun, rivers*. Philadelphia: C. and A. Conrad.

Reuss, M. 1998. *Designing the bayous: The control of water in the Atchafalaya basin, 1800–1995*. Alexandria, VA: Office of History, U.S. Army Corps of Engineers.

Richter, B. D., R. Mathews, D. L. Harrison, and R. Wiggington. 2003. Ecologically sustainable water management: Managing river flows for ecological integrity. *Ecological Applications* 13:206–24.

Scarpino, P. V. 1985. *Great River: An environmental history of the Upper Mississippi, 1850–1950*. Columbia: University of Missouri Press.

Schramm, H. L. 2004. Status and management of Mississippi River fisheries. In *Proceedings of the 2nd International Symposium on the Management of Large Rivers for Fisheries*, vol. 1, ed. R. L. Welcomme and T. Petr, 301–34. RAP Publication 2004/16. Bangkok, Thailand: FAO Regional Office for Asia and the Pacific.

Schoolcraft, H. R. 1953. *Schoolcraft's narrative journal of travels: Through the northwestern regions of the United States, extending from Detroit through the great chain of American lakes to the sources of the Mississippi River, in the year 1820*. Edited by M. L. Williams. East Lansing: Michigan State University Press.

Turner, R. E. 1997. Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. *Estuaries* 20:1–13.

Twain, M. 1883 (1992). *Life on the Mississippi*. New York: Book of the Month Club.

Tweet, R. D. 1983. *History of transportation on the upper Mississippi and Illinois rivers.* U.S. Army Engineer Water Resources Support Center, Navigation History NWS–83-6. Washington, DC: U.S. Government Printing Office.

U.S. Geological Survey. 1999. *Ecological status and trends of the Upper Mississippi River system, 1998.* Long Term Resource Monitoring Program 99-T001. Washington, DC: U.S. Government Printing Office.

Upper Mississippi River Conservation Committee. 2000. *A working river and a river that works.* Rock Island, IL: Upper Mississippi River Conservation Committee.

Wang, M., and D. D. Adrian. 1998. Wetland loss in coastal Louisiana. *International Journal of Sediment Research* 13:1.

Winger, P. V., and P. J. Lasier. 1998. Toxicity of sediment collected upriver and downriver of major cities along the Lower Mississippi River. *Archives of Environmental Contamination and Toxicology* 35:213–17.

Chapter Eight. The Murray-Darling: Stumbling in the Waltz

Allison, G. B., P. G. Cook, S. R. Barnett, G. R. Walker, I. D. Jolly, and M. W. Hughes. 1990. Land clearance and river salinisation in the western Murray basin, Australia. *Journal of Hydrology* 119:1–20.

Arthington, A. H. 1996. The effects of agricultural land use and cotton production on tributaries of the Darling River, Australia. *GeoJournal* 40:115–25.

Arthington, A. H., and B. J. Pusey. 2003. Flow restoration and protection in Australian rivers. *River Research and Applications* 19:377–95.

Boulton, A. J., and L. N. Lloyd. 1992. Flooding frequency and invertebrate emergence from dry floodplain sediments of the River Murray, Australia. *Regulated Rivers: Research and Management* 7:137–51.

Bowling, L. C., and P. D. Baker. 1996. Major cyanobacterial bloom in the Barwon-Darling River, Australia, in 1991, and underlying limnological conditions. *Marine and Freshwater Research* 47:643–57.

Braaten, R., and G. Gates. 2003. Groundwater-surface water interaction in inland New South Wales: A scoping study. *Water Science and Technology* 48:215–24.

Chen, X. Y. 1995. Geomorphology, stratigraphy and thermoluminescence dating of the lunette dune at Lake Victoria, western New South Wales. *Palaeogeography, Palaeoclimatology, Palaeoecology* 113:69–86.

Crabb, P. 1988. Managing the Murray-Darling basin. *Australian Geographer* 19:64–84.

Dyer, F. J. 2002. Assessing the hydrological changes to flood plain wetland inundation caused by river regulation. In *The structure, function and management implications of fluvial sedimentary systems.* IAHS Publication 276, 245–53. Wallingford, UK: International Association of Hydrological Sciences.

Fisher, T. 1996. Fish out of water: The plight of native fish in the Murray-Darling. *Fish and Fisheries Worldwide* 24:17–24.

Goss, K. F. 2003. Environmental flows, river salinity and biodiversity conservation: Managing trade-offs in the Murray-Darling basin. *Australian Journal of Botany* 51:619–25.

Harris, G. 1995. Eutrophication—are Australian waters different from those overseas? *Water* 2:9–12.

Herczeg, A. L., H. James Simpson, and E. Mazor. 1993. Transport of soluble salts in a large semiarid basin: River Murray, Australia. *Journal of Hydrology* 144:59–84.

Hillman, T. J., and Quinn, G. P. 2002. Temporal changes in macroinvertebrate assemblages following experimental flooding in permanent and temporary wetlands in an Australian floodplain foreset. *River Research and Applications* 18:137–54.

Humphries, P. L., A. J. King, and J. D. Koehn. 1999. Fish, flows and flood plains: Links between freshwater fishes and their environment in the Murray-Darling River system, Australia. *Environmental Biology of Fishes* 56:129–51.

Jenkins, K. M., and A. J. Boulton. 2003. Connectivity in a dryland river: Short-term aquatic microinvertebrate recruitment following floodplain inundation. *Ecology* 84:2708–23.

Jensen, A. 1998. Rehabilitation of the river Murray, Australia: Identifying causes of degradation and options for bringing the environment into the management equation. In *Rehabilitation of rivers: Principles and implementation*, ed. L. C. de Waal, A. R. G. Large, and P. M. Wade, 215–36. Chichester, UK: John Wiley.

Langford-Smith, T., and J. Rutherford. 1966. *Water and land: Two case studies in irrigation.* Canberra: Australian National University Press.

Leslie, D. J. 2001. Effect of river management on colonially-nesting waterbirds in the Barmah-Willewa Forest, south-eastern Australia. *Regulated Rivers: Research and Management* 17:21–36.

Low, T. 2002. *Feral future: The untold story of Australia's exotic invaders.* Chicago: University of Chicago Press.

MacNally, R., and G. Horrocks. 2002. Habitat change and restoration: Responses of a forest-floor mammal species to manipulations of fallen timber in floodplain forests. *Animal Biodiversity and Conservation* 25:41–52.

McGinness, H. M., M. C. Thoms, and M. R. Southwell. 2002. Connectivity and fragmentation of flood plain—river exchanges in a semiarid, anabranching river system. In *The structure, function and management implications of fluvial sedimentary systems.* IAHS Publication 276, 19–26. Ottawa: International Association of Hydrological Sciences.

Pigram, J. J., and W. F. Musgrave. 2002. Sharing the waters of the Murray-Darling basin: Cooperative federalism under test in Australia. In *Conflict*