Naturalization of the Flood Regime in Regulated Rivers

The case of the upper Mississippi River

Richard E. Sparks, John C. Nelson, and Yao Yin

The Upper Mississippi River System (Figure 1) includes the Illinois and the upper Mississippi Rivers (UMRBC 1981)—two of the very few large floodplain–river ecosystems in the developed world that still retain seasonal flood pulses and half their original floodplains (50% of the original combined floodplain area of 1,038,000 ha along the two rivers remains unleveed [Mills et al. 1966, Delaney and Craig 1997]). These are working rivers: 126 million tons of cargo are transported annually on 2167 km of navigable waterways (USACE 1997). Most of the cargo comprises corn, soybeans, and wheat shipped from the Corn Belt of the United States to New Orleans for shipment overseas, prompting Hoops (no date) to characterize the Upper Mississippi River System as "a river of grain."

After a century of draining wetlands for agriculture, preventing floods with levees, and maintaining water levels for navigation with dams, relaxation of constraints on both high and low water levels is a radical idea

Despite levees and modifications for navigation, the rivers and their floodplains still form a complex mosaic of main and side channels, floodplain lakes, and seasonally inundated wetlands that support 485 species of mussels, fishes, amphibians, reptiles, birds, and mammals, including nine species that are federally listed as threatened or endangered and 50 that are listed as rare, threatened, or endangered by the five states of the Upper Mississippi River System (USACE 1997). More than 40% of North America's migratory waterfowl and shorebirds depend on habitat provided by the Upper Mississippi River System. One thousand licensed commercial fishermen take 5.5 million kg of fish worth $2.5 million annually (UMRCC 1992–1995, Williamson 1996). From 1988 through 1990, 8 × 10^6^ kg of mussel shells from the rivers, worth $9.6 million, were shipped to marine pearl farms around the Pacific Rim, where the river shells were cut and rounded into nuclei to be inserted into pearl oysters (Thiel and Fritz 1993). The economic value of river-based recreation (e.g., boating, hunting, fishing, bird watching, and sight-seeing) dwarfs the value of commercial harvests: $1.2 billion and 18,000 jobs are generated in the US economy by outdoor recreation in the Upper Mississippi River System (Carlson 1993). Many of the commercial and recreational uses of the rivers depend on the richness of species and the high biological productivity of the rivers, which depend in turn on the annual advance and recession of floods (Bayley 1995, Sparks 1995).

In this article, we assess the degree of change in the flow regimes of the Illinois and upper Mississippi rivers and describe ongoing efforts to restore or naturalize the regimes. We begin by describing the natural pattern of water level variation and its importance, both to organisms and ecosystem processes, prior to large-scale human alteration. Next, we explain how navigation dams, drainage of uplands and floodplains, and changes in precipitation patterns have altered the flood regimes. (Navigation dams are designed to pass great floods, such as the Midwest flood of 1993—a natural disturbance that killed trees on the floodplains, reset succession, and affected many other taxonomic groups and ecosystem processes.)

We next describe several contrasting perspectives regarding threats to the two rivers and discuss the feasibility of naturalizing or restoring water and sediment regimes. We use the National Research Council (NRC 1992, p. 18) definition of restoration, which has fairly stringent re-

---

Richard E. Sparks (e-mail: rsparks@netins.net) is director of the River Research Laboratory, Havana, IL 62644, a unit of the Center for Aquatic Ecology, Illinois Natural History Survey. John C. Nelson (e-mail: John_C_Nelson@usgs.gov) is a forest ecologist at the Great Rivers Field Station, Alton, IL 62002. Yao Yin (e-mail: Yao_Yin@usgs.gov) is a forest ecologist at the Environmental Management Technical Center, Onalaska, WI 54650, a unit of the Biological Resources Division of the US Geological Survey.

quirements: returning an ecosystem to a close approximation of a condition that existed prior to human alteration. Naturalization has less stringent requirements: The goal is to shift some components of an altered ecosystem (e.g., riparian vegetation) closer to a natural condition, while maintaining or enhancing existing economic and social uses of the ecosystem (Rhoads and Herricks 1996). Finally, we assess several approaches to flow naturalization, including controlled flooding and dewatering in leveed compartments on the floodplain, and altered dam operations on the mainstem river. These approaches are applicable to other rivers with navigation dams and leveed floodplains.

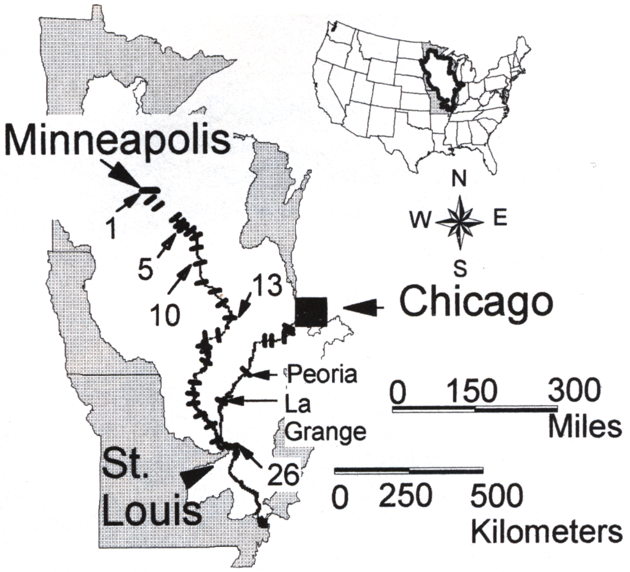

Figure 1. The Upper Mississippi River System. Following the convention of the US Army Corps of Engineers, the navigation dams on the Illinois River are named and those on the upper Mississippi River are numbered. Only a few dams are labeled to avoid crowding the figure.

Natural flooding

The relatively undisturbed flood regime along the Illinois and upper Mississippi Rivers is documented by daily readings of water levels at several locations, beginning in 1878 (Figures 2 and 3). Drainage of the floodplains and uplands in the corn belt of the Midwest had already begun in the 1870s but was not yet extensive. In the 1880s, upland drainage for agriculture accelerated, increasing the rate of delivery of seasonal runoff into the Illinois River so that water entered the river and its floodplain more rapidly and nearly simultaneously from many tributaries (Kofoid 1903). As a result, the rate of rise of the spring flood in the Illinois River and on its floodplain increased 22%. However, the rate at which the spring flood receded remained nearly the same because the intact floodplain had an enormous water-storage capacity (1813 square km filled to a depth of several meters). Because of the extremely shallow downstream slope of the Illinois River and its floodplain (only 2 cm/km [Cooley 1891 as cited in Kofoid 1903]), the water moved slowly down to the single exit into the Mississippi River.

Two additional factors were important in retarding the recession of the flood on the Illinois River. First, the timing of the spring flood in the upper Mississippi River usually overlapped with the flood in the Illinois. As a result, the high water in the Mississippi acted as a hydraulic dam, slowing the drainage of the lower 250 km of the Illinois River and even backing water up the Illinois (Cooley 1891 as cited in Kofoid 1903, Akanbi and Singh 1997). Second, the stems and leaves of living vegetation on the floodplain and shoreline, and the dead woody debris in the bottom of the river and along the banks, increased the water flow resistance and slowed the flow in the main channel of the river and in the channels that carried water off the floodplain (Dawson and Charlton 1988, Pitlo and Dawson 1990, Maser and Sedell 1994).

The lengthy flood was important for the fish fauna of the river. A long (six weeks or more), slowly receding spring flood is critically important to the many fishes that use the expanded littoral zones of the floodplain lakes and the inundated floodplain itself as spawning and nursery sites. Basses, crappies, and sunfishes (Centrarchidae) build nests in shallow water, and catfishes (Ictaluridae) build nests or use natural cavities (undercut banks, root masses of trees, burrows of muskrats and beavers) for their eggs and newly hatched young,

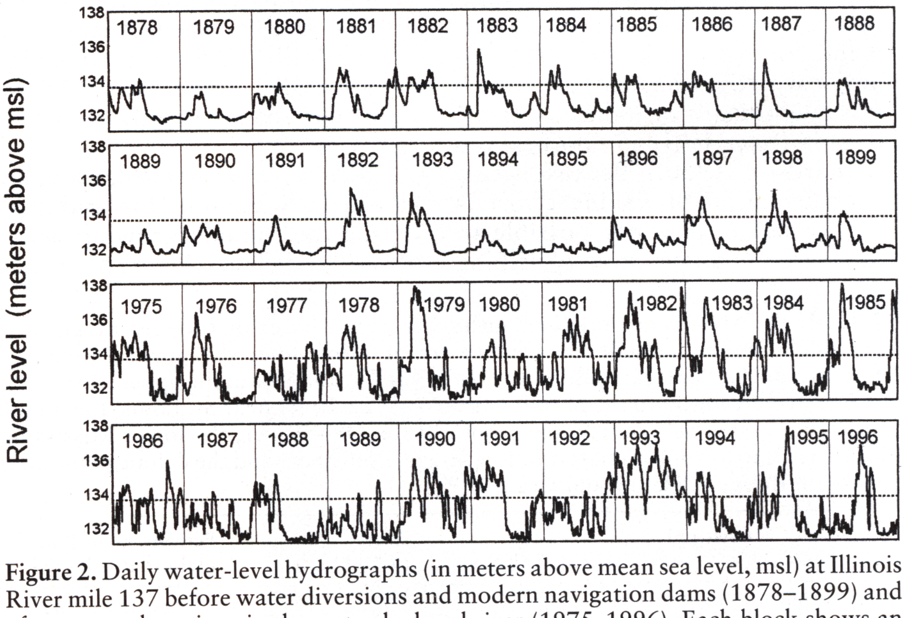

Figure 2. Daily water-level hydrographs (in meters above mean sea level, msl) at Illinois River mile 137 before water diversions and modern navigation dams (1878–1899) and after many alterations in the watershed and river (1975–1996). Each block shows an entire year, from 1 January to 31 December. In the recent period, river levels are noticeably more erratic (spikier), major floods are higher and more frequent, and there are fewer years with low, stable water levels during the summer growing season. Low, stable water levels are essential for moist-soil plants and aquatic vegetation growing in permanent floodplain lakes and backwaters. The horizontal line indicates a flood elevation at which economic damage occurs.

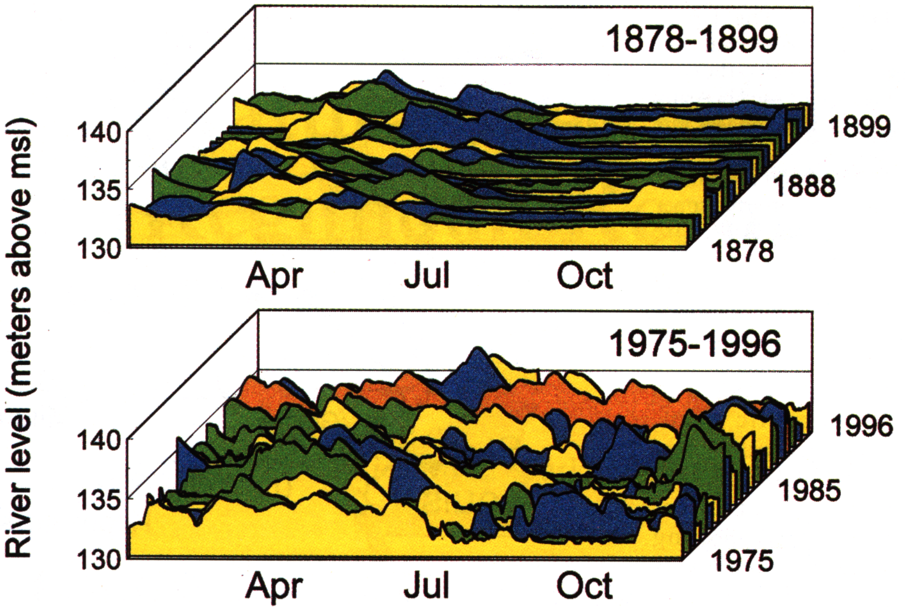

Figure 3. Same data as in Figure 2, but years are widened and stacked one behind the other to emphasize the low-flow "valley" that typically occurred during the summer growing season prior to 1900, but not in more recent years.

which can be stranded if the water drops too quickly (Pflieger 1975, Sparks 1995).

The increase in the flood's rate of rise, beginning in the 1880s, did not adversely affect fish recruitment and growth, judging by the commercial fish yield, which increased from 2.7 million kg in 1894 to 6.4 million kg in 1899. These increases undoubtedly reflect the growing market demand for fish, including the common carp (*Cyprinus carpio*), which was intentionally introduced into the Illinois River in 1885 (Forbes and Richardson 1920). Because good documentation of fishing effort is not available, it is not possible to calculate yields per unit of fishing effort. However, the total yields indicate that fish remained exceptionally abundant through the turn of the century. Many of the fishes that we consider game fish today were harvested commercially in the late nineteenth century; for example, people earned a living by catching largemouth bass (*Micropterus salmoides*) with cane poles for the local market. In 1897, the fish markets in the small Illinois River town of Havana handled a remarkable 15,930 kg of bass commercially (Cohen et al. 1899).

Once the flood receded, water levels generally remained low and stable during the summer growing season for wetland plants (Figure 3). In most years, water levels rose in the fall, making the summer's production of seeds and tubers accessible to flocks of waterfowl that were migrating south to their wintering grounds. Fish also used fall floods to access wintering areas, where the water was deep enough so that it would not freeze to the bottom and current velocities were low enough that fish did not have to expend energy swimming (Sparks 1995).

Table 1. The Mississippi is divided into six segments based on the percentage of the floodplain that is leveed: the headwaters in Minnesota; the upper Mississippi (north) from St. Paul, Minnesota, to Dam 13 at Clinton, Iowa; the upper Mississippi (south) from Clinton to the mouth of the Missouri River near St. Louis; the middle Mississippi from St. Louis to the mouth of the Ohio River; the lower Mississippi from the Ohio to approximately Baton Rouge, Louisiana; and the deltaic plain south of Baton Rouge (Delaney and Craig 1997).

Segment of Mississippi River (MR)	Length (km)	Area (× 1000 ha)	Percentage of floodplain that is leveed
Headwaters	805	133	Less than 0.01
Upper MR, north	554	201	3
Upper MR, south	526	407	53
Middle MR	314	268	82
Lower MR	1167	10,117	93
Deltaic plain	399	1214	96
Total	3765	12,340	90

Although the upland drainage prior to 1900 apparently had little effect on biota in the floodplains of the Illinois River, subsequent changes in the uplands and in the rivers did. Changes in the mean low water *level* (rather than flow) and in the seasonal timing, duration, frequency, and rate of fall of the floods turned out to be particularly important to the entire river–floodplain ecosystem in the Illinois and upper Mississippi Rivers.

Effects of agricultural levees and navigation dams

In the well-watered Midwest, humans have worked for over a century to drain water off the land as rapidly as possible and to use floodplains for dryland agriculture. By 1930, approximately half of the floodplain along the Illinois River and the portion of the upper Mississippi bordering Illinois and Iowa was leveed and drained for agriculture (Scarpino 1985, Thompson 1989). The degree of leveeing varies from north to south: Over 90% of the floodplain remains unleveed in Minnesota and Wisconsin, whereas more than 90% of the floodplain is leveed in Arkansas, Mississippi, and Louisiana (Table 1). Not only is water delivered to the mainstem rivers much more rapidly than in the 1870s because of upland drainage, but also the capacity of the floodplain to store and slowly convey floodwater downstream has been reduced by the levees that constrict the floodplain. The modern floodplain acts less like a reservoir and more like a constricted channel. The result is a water-level hydrograph that is "spikier" at both high and low river stages (Figures 2 and 3).

During the 1930s, 28 low navigation dams were constructed on the Mississippi River upstream from St.

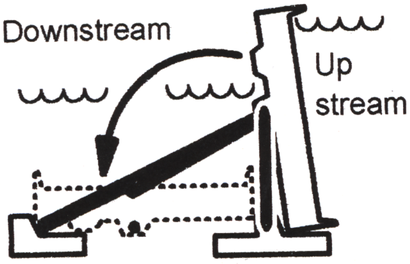

Figure 4. Operation of a wicket dam. During high water, the wickets pivot down onto the bottom of the river (dashed outline).

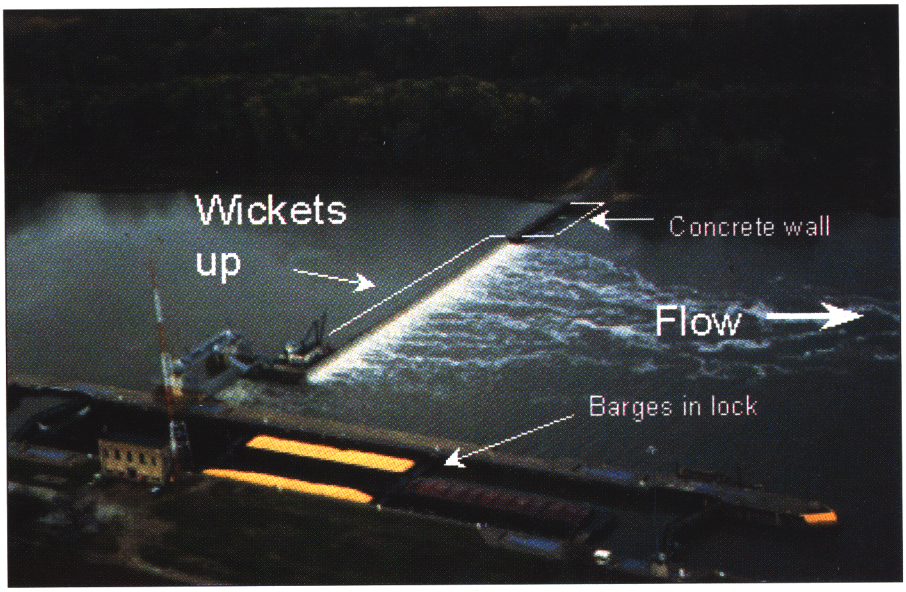

Figure 5. The La Grange Dam (Illinois river mile 80.2), with the wickets raised. The river is flowing over the top of the wickets.

Louis, and five were constructed on the Illinois River. In contrast to high dams, which store flood water, the navigation dams maintain a minimum depth of 2.7 m for commercial boat traffic during low-flow periods; the navigation dams do not stop infrequent, great floods or most spring floods. In fact, during floods the dam gates are lifted out of the water or lowered to the bottom of the river (e.g., at Peoria and La Grange on the Illinois River; Figures 4 and 5) to avoid increasing flood heights and flood damage upstream of the dams. Many of the dams on the upper Mississippi have relatively low earthen berms running from the gates to the river bluff that are designed to be overtopped during major floods. During the height of the spring flood, the Illinois is open from the Starved Rock Dam to the confluence with the Mississippi, a distance of 372 km, and the Mississippi is open from Dam 19 to the sea, a distance of 2156 km (there are no dams south of St. Louis)—thus allowing fishes, including the American eel (*Anguilla rostrata*), which spawns in the Sargasso Sea east of Cuba, to migrate. Although the navigation dams do not stop major floods or fish migration during floods, they do alter the seasonal water level pattern and permanently inundate portions of the floodplain.

Permanent effects of navigation dams. Many of these dams permanently inundate portions of the floodplain immediately upstream of the dam by not allowing the river to drop as low as it once did during the summer low-flow season (Sparks 1995). Permanent inundation of the floodplain following construction of the dams killed vegetation, including forests, which were replaced in many areas by submersed aquatic vegetation (Yeager 1949, Mills et al. 1966, Nelson et al. 1996). Even in floodplain areas that still dry out during the summer, the water table rose sufficiently when the dams went into operation that species of trees that require unsaturated soil during the growing season were killed (Figure 6; Yin and Nelson 1996, Yin et al. 1997).

Effects of dams on seasonal water regimes. By not letting the rivers get as low as they once did, navigation dams typically reduce the range of water-level variation over a distance ranging from one-half to two-thirds of the distance upstream to the next dam. Moreover, the gates are operated to pass moderate floods without raising water levels up-

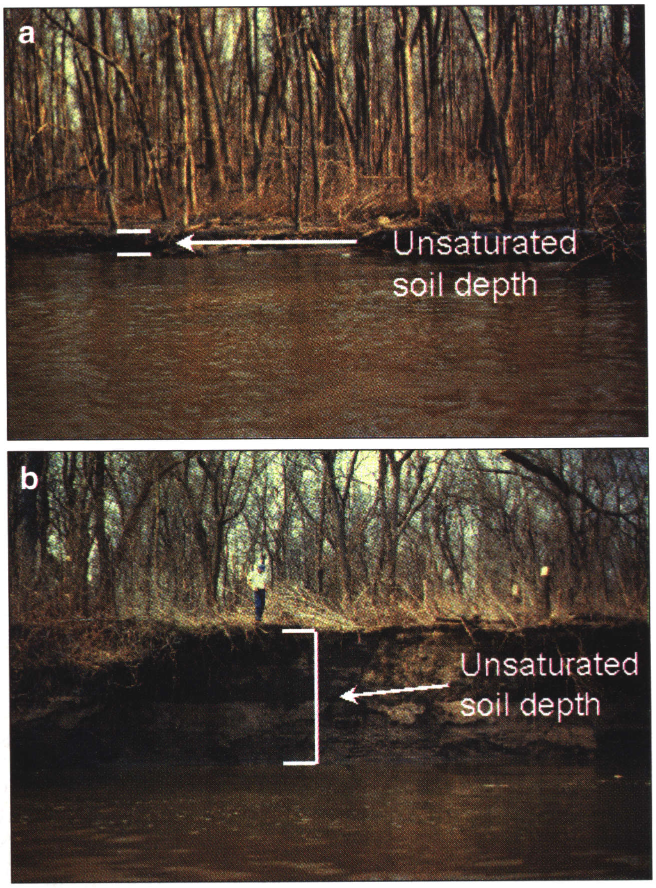

Figure 6. Relationship between soil surface and water surface on the same day in Reach 26 of the upper Mississippi River. (**a**) At Mississippi River mile 205, four miles upstream from Dam 26, the river is not allowed to drop as low as it once did; consequently, the soil surface is close to the water surface. Few tree species tolerate such a shallow depth of unsaturated soil. (**b**) Thirty-six miles upstream from Dam 26, the unsaturated soil depth is much greater.

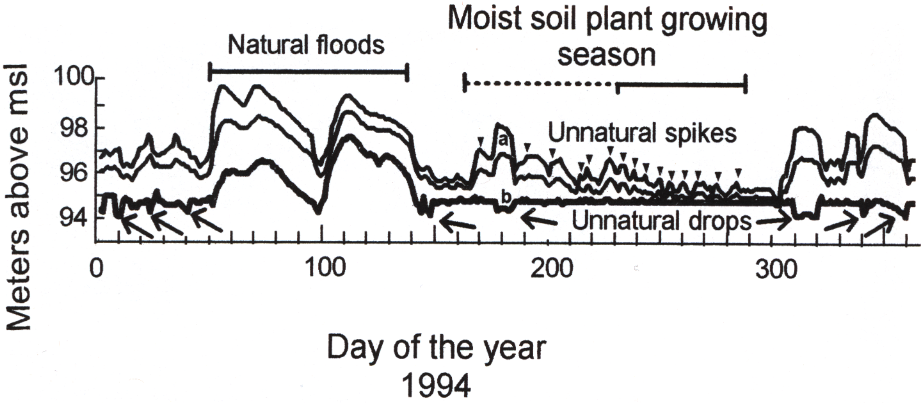

Figure 7. 1994 daily water levels within the La Grange Reach of the Illinois River, illustrating spikes and drops in water levels caused by dam operations. One can imagine standing on the La Grange Dam and looking upstream several miles at the water surface. The lowest (thick) line is the water elevation closest to the observer (Illinois River mile 80, at the dam), the middle line is in the middle distance (38 miles upstream from the dam), and the upper line is farthest upstream (78 miles). During low to moderate floods (e.g., in June, indicated by a) water levels near the dams actually drop (indicated by b and by arrows) because wickets are lowered or gates are opened (La Grange Dam has both). Unnatural drops in water levels in December and January (arrows) can kill fish in their winter refuges. Unnatural rises (spikes indicated by inverted triangles) caused by releases from the upstream dam during the summer growing season can drown plants growing on moist soil. The spikes smooth out by the time they reach the dam. The dam has no effect on the pattern of the major spring flood (two crests, March through May).

stream, further reducing natural variation. The dam operating procedures at the first three dams on the upper Mississippi River upstream from St. Louis and at the La Grange and Peoria dams on the Illinois River often invert the natural water regime: The floodplain and backwaters drain during moderate floods in the spring and fall, and they flood during the summer growing season (Figure 7; Sparks 1995).

Short-term fluctuations. The navigation dams at La Grange and Peoria on the Illinois River cannot control water levels as precisely as gates; these dams consist of individual wickets or panels that are either entirely up or down, whereas individual gates in other navigation dams can be raised or lowered incrementally (Figures 4 and 5). The wickets are not raised until water levels have dropped low enough so that water upstream of the wickets will be at least 61 cm higher than the water downstream. This procedure is necessary to keep the wickets pressed firmly against their downstream supports. Consequently, water levels near the wicket dams first drop, then rise quickly when the wickets are raised. Additional short-term fluctuations may occur if the operation of the wicket dams cannot be coordinated perfectly. For example, when the upstream dam at Peoria is raised but the downstream dam at La Grange cannot be raised on schedule because of equipment problems, the La Grange Reach downstream of Peoria drains partially, dropping water levels between La Grange and Peoria excessively.

Although most public attention focuses on major floods, which have been increasing in frequency and height (Figure 2), ill-timed minor floods and small drops in water levels occur every year in the upper Mississippi and Illinois Rivers, damaging floodplain vegetation and fishes. Small, abrupt rises during the summer growing season drown the moist-soil plants that provide seeds and tubers for migratory waterfowl in the fall (La Grange Reach; Figure 8). Abrupt drops at any time of the year can strand and kill fish in shallow backwaters and floodplain lakes (Figure 8). Even if the backwaters do not drain completely, fish may die from low dissolved oxygen or temperature extremes in shallow water.

The Midwest flood of 1993

Major, infrequent floods arise from infrequent natural causes, such as unusually heavy rains (the Midwest flood of 1993) or rapid melting of an unusually thick accumulation of snow (the 1997 flood on the Red River of the North in the Dakotas, Minnesota, and Manitoba). In addition, alterations in watersheds, floodplains, and rivers themselves contribute to the well-documented trend of increasing flood heights for a given flow (Belt 1975, Leopold 1994). Long-term meteorological trends are also contributing factors: Rainfall during the four-month flood season (March–June) in the upper Illinois River in the past 20 years is 25% higher than it was in the previous 60 years (Singh and Ramamurthy 1990). And 30-year shifts in flood frequency and magnitudes in the upper Mississippi have been related to changes in the prevailing patterns of atmospheric circulation (Knox 1985). The rains of 1993 lasted well beyond the normal rainy season of April–June, with consequences that extended from upland farms to the floodplains of the Mississippi and beyond, to the Gulf of Mexico.

Hydrological characteristics. The Midwest flood of 1993 lasted an unusually long time, extending into the summer growing season, when water levels are normally low (Figures 8 and 9). The flood began in April, during the normal flood season, but multiple peaks continued through the entire summer, and the river did not drop below flood stage at St. Louis until 30 September (Figure 8; Southard 1995). In terms of peak flood elevation and peak daily flow, the 1993 flood had a recurrence interval of greater than 100 years at St. Louis, but of only 10–50 years downstream of St. Louis at Chester and Thebes, Illinois (Parrett et al. 1993). However, in terms of mean daily flows sustained for 120 consecutive days, the recurrence interval exceeded 100 years at all three gaging stations (Southard 1995). Another indication of the extreme duration of the 1993 flood is that whereas only 24 of the 60 gaging stations used by Southard (1995) set new records for sustained three-day flows, 47 of the stations set new records for 120-day flows.

Effects on floodplains and the Gulf of Mexico. The heavy rains fell on Midwestern upland prairie soils that had high nutrient concentrations even before annual additions of commercial fertilizer. Consequently, nutrient-rich sediments were deposited on the remaining unleveed floodplains of the mainstem rivers and in leveed areas where levees broke; they were also delivered to the Gulf of Mexico. In the flooded floodplains, soil microbial processes, including decomposition of organic matter, were reset to high levels, and nutrient stores will probably be well in excess of plant growth requirements for several years (Spink et al. 1998).

If more of the floodplains and Mississippi Delta had been allowed to flood, more nutrients would have been retained and fewer would have been injected directly into the Gulf, where nutrient concentrations five to ten times higher than in previous years caused an order-of-magnitude increase in phytoplankton near the water's surface (Rabalais et al. 1998). When the phytoplankton died and sank, the oxygen demand from decomposition contributed to a doubling of the areal extent of hypoxic water on the bottom of the Gulf, which threatens valuable fishes, crustaceans, and mollusks (Figure 8; Rabalais et al. 1998). Despite a reduction in nitrogen loading from the river in the years following the 1993 flood, the hypoxic zone has not shrunk to its pre-1993 dimensions, perhaps indicating that nutrients delivered in 1993 are being recycled from the Gulf sediments (Rabalais et al. 1998).

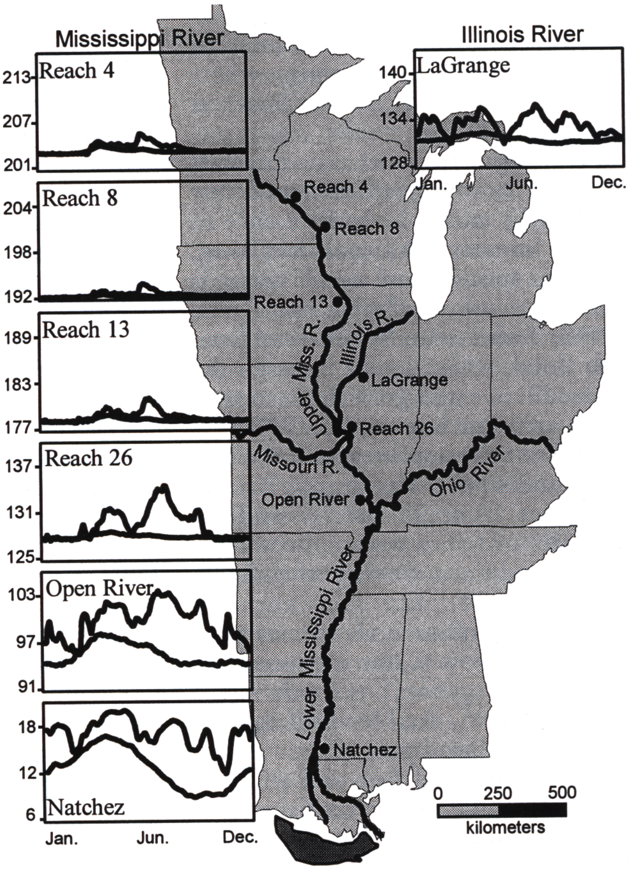

Figure 8. Water-level hydrographs (feet above mean sea level) at six locations along the Mississippi River and one location on the Illinois River. The 1993 flood is the upper line in each hydrograph; the lower line is the average daily water level since the navigation dams were completed in the 1930s. The shaded area in the Gulf of Mexico indicates the extent of the hypoxic zone (Rabalais et al. 1998). Data supplied by the St. Paul, MN; Rock Island, IL; St. Louis, MO; and Vicksburg, MS districts of the US Army Corps of Engineers.

Effects on populations. The duration of flooding and the resulting biological impacts varied from upstream to downstream and with land elevation within the floodplain. Flood duration was critical; if soils are saturated long enough for anoxic conditions to develop, the roots of terrestrial plants eventually die and water is no longer transported upward to stems and leaves. A number of mature trees in the floodplain had brown, drying leaves in 1993, even though they were standing in water—as though a drought, rather than a flood, were occurring! Smaller trees generally fared less well than taller trees of the same species because their crowns were completely covered by water (Yin et al. 1994). Mortality of American elm (*Ulmus americana*) was high because elms are generally young understory trees. (American elm succumbs to Dutch elm disease when it reaches maturity.) If any mature elms had been present, they probably would have survived. Trees growing on natural levees, swells, and terraces in the floodplain can tolerate brief floods during the growing season, but the critical duration was clearly surpassed in the vicinity of St. Louis and downstream to the Ohio River, where virtually all individuals of the following species were killed: dogwood (*Cornus* spp.), eastern redbud (*Cercis canadensis*), hackberry (*Celtis occidentalis*), pin oak (*Quercus palustris*), shagbark hickory (*Carya ovata*), and shellbark hickory (*Carya laciniosa*). Mortality was even high in some stands of flood-tolerant eastern cottonwood (*Populus deltoides*) and sycamore (*Platanus occidentalis*).

During the winter following the flood, the bark of many sycamore trees fell off the base of the trees below the flood line, perhaps because of water freezing under the bark. These damaged sycamores are now highly susceptible to disease and insect infestation. Woodpeckers (Picidae) are thriving, using standing dead trees to feed and to excavate nest cavities that are used subsequently by raccoons (*Procyon lotor*), squirrels (Sciuridae), Carolina wrens (*Thryothorus ludovicianus*), owls (Tytonidae and Strigidae), prothonotary warblers (*Protonotaria citrea*), tree swallows (*Iridoprocne bicolor*), wood ducks (*Aix sponsa*), and other cavity nesters.

Life-history traits, particularly mobility and degree of adaptation to flooding, were critical in determining the effects of flooding on various taxonomic and functional groups of organisms. Several species of aquatic plants in the northern part of the river survived by growing upward into the lighted zone as the flood rose, but aquatic vegetation was eliminated farther south (Spink and Rogers 1996). Conversely, fugitive species (*sensu* Hutchison 1951), which are restricted to ephemeral habitats that often result from disturbance events, such as flooding, benefited from the flood (Smith et al. 1998, Sparks and Spink 1998). For example, the decurrent false aster (*Boltonia decurrens*), a perennial forb that occurs principally along the Illinois River, requires regular flooding to remove competitors for light and to provide fresh mudflats on which seeds can germinate. This rare, threatened species increased following the flood of 1993, particularly where flooding was most severe (Smith et al. 1998).

Among the animals, mussels showed no adverse effects, probably because it makes little difference to these mostly channel-dwelling, benthic species how much water is passing overhead (Miller and Payne 1998). Fishes actually benefited from the flood, which lasted through the reproductive and growth seasons of both early and late spawners (Sparks 1996). At the confluence of the Illinois and upper Mississippi Rivers, juveniles from 52 species and 15 families of fishes were collected on the floodplain during the flood (Maher 1994). The proportion of young fish of several species that nest in shallow water increased, as did these species' growth rates (Bartels 1995, Raibley and Sparks 1997). The flood provided access to freshly inundated firm soil and terrestrial vegetation for sunfishes and basses, which require firm substrates for their nests. The permanent floodplain lakes and backwaters often have soft, muddy bottoms that are unsuitable for nests. Young fishes produced during 1993 are likely to affect aquatic communities (as well as fishing opportunities) for several years through predator–prey and competitive interactions.

Community-level consequences. The community-level consequences of the 1993 flood were qualitatively different from those of shorter-duration floods. Trees and shrubs were killed from the roots upward during this flood, so they could not put out new leaves or resprout from belowground parts, as they might have done following a briefer flood. The entire understory was eliminated in substantial portions of the floodplains within approximately 150 km of St. Louis. Consequently, no saplings were available to grow following the death of the overstory trees (cottonwoods). Such saplings usually are available when mature trees die from other causes or are downed by wind. Species with some individuals growing on river bluffs or terraces above the floodline and whose seeds are abundant, light, and dispersed aerially (e.g., cottonwoods), might be expected to win the race to repopulate the floodplain. In contrast, several species of native oaks (including pin oak) and pecans (*Carya illinoensis*) may not reestablish stands because surviving seed sources are now very rare and far apart and because these species produce large numbers of seeds infrequently. Moreover, these seeds have relatively short periods of viability and, being heavy, are dispersed over relatively short distances.

Pioneer tree species (willow and cottonwood) had persisted in the St. Louis-to-Ohio River reach of the Mississippi because channel meandering alternately scoured and rebuilt portions of the floodplain. However, since 1927, when the river channel was stabilized for navigation, the forests had been changing to silver maple (*Acer saccharinum*) and box elder (*Acer negundo*). After the 1993 flood, seedlings were predominantly willow and cottonwood. The flood substituted for channel meandering in resetting succession (Yin 1998).

As events in 1995 demonstrated, the successional trajectory of the floodplain plant community has been and will continue to be extremely sensitive to the effects of subsequent floods in the years following the 1993 flood. Both cottonwood and silver maple seedlings are vulnerable to frequent, low-level floods until they are tall enough that their leaves are above the floodline. Although it was of much shorter duration, the flood of 1995 was higher in some parts of the floodplains of the upper Mississippi than the 1993 flood, and it killed extensive tracts of seedling trees. Forest regeneration along the upper Mississippi may be continuously reset until a series of drought years and low river levels allow trees to grow sufficiently tall to survive subsequent flooding. However, if droughts dry the standing and downed timber left by the 1993 flood sufficiently to facilitate fires, existing floodplain prairies could expand. Periodic fires probably helped to maintain prairies on the floodplains and adjacent bluffs through 1817, when surveyors' records indicate that 41% of the floodplain at the confluence of the Illinois and upper Mississippi Rivers consisted of prairie, rather than forest (Nelson et al. 1994). Prescribed burning, as well as managed flooding, might therefore restore the native plant communities of the floodplains of the large Midwestern rivers (Nelson and Sparks 1998).

Dead wood along the banks and edges of the floodplain forests is carried away during subsequent floods, becomes waterlogged, and then sinks or lodges elsewhere. Since 1993, annual floods in the upper Mississippi River have been transporting noticeably more dead wood downstream, clogging dam gates and locks but also providing solid substrate for many freshwater invertebrates and a source of carbon for marine invertebrates as far distant as the ocean (Maser and Sedell 1994).

Managed floods

Infrequent great floods will continue to occur in the floodplains of the Illinois and upper Mississippi Rivers because navigation dams do not stop floods, because levees have design limits, and because unusually heavy and protracted rains will come again. In contrast, humans will determine whether seasonal small floods and low water levels will follow the natural pattern (to which the biota are adapted) or become increasingly erratic. One approach to re-creating the natural water-level pattern has been to isolate relatively small parcels of floodplain behind low levees that can exclude small rises in water level (the "spikes" in Figure 7) during the summer growing season. Newer approaches include modification of navigation dam operations to naturalize water-level regimes and thereby benefit plants and animals over extensive reaches of river and floodplain between the navigation dams.

Controlled seasonal flooding of floodplain compartments. Federal and state waterfowl refuges, public hunting areas, and private waterfowl hunting clubs along both the Illinois and upper Mississippi Rivers use low levees as well as pumps or gates to expose mudflats during summer, thereby encouraging the growth of moist-soil plants. Water levels are then raised during the fall to the preferred shallow feeding depth of dabbling ducks (in contrast to diving ducks, which find their food by diving in deeper water). The levees surround floodplain compartments that can be drained by gravity, if the river is low enough, or with pumps, if it is not. The low levees and gates exclude the frequent small fluctuations in the river that would drown the moist-soil plants. In the fall, water is pumped into the compartments from the river, or the gates are opened if the river rises. The flooding pattern is usually tailored to the requirements of native species of moist-soil plants, although some managers sow Japanese millet or corn to attract and feed waterfowl. The requirements of the various food plants are sufficiently well known that management manuals have been developed (Fredrickson and Taylor 1982).

The low levees are overtopped by the typical spring flood, allowing fish access to the compartments to spawn. However, fisheries managers are concerned that adult and young-of-the-year fishes will not be safely returned to the river when the compartments are drained or pumped out. Another issue is whether the floodplain compartments provide winter refuges for fish.

Periodic controlled drawdowns. Drying and compaction of sediments every few years might restore backwaters that are now filled with watery sediments and devoid of submersed aquatic vegetation. These drawdowns would be more extreme than the seasonal water manipulations described above and would be done infrequently (Theiling 1995). For example, at the Chautauqua National Wildlife Refuge on the Illinois River, the floodplain lake was pumped dry during the summer of 1994 to rebuild the low levees and to construct gates and spillways. Seventy-seven species of aquatic and moist-soil plants germinated that had not been seen on this area since the 1988–1989 drought, and submersed aquatic vegetation appeared in several small pools that formed in the tread ruts of construction machinery. This 1619 ha area attracted a peak of 460,000 waterfowl on 29 November 1994—45% of the total migrating population in a censused area of the upper Mississippi Flyway that includes the rivers and their floodplains and backwaters along 422 km of the upper Mississippi and 351 km of the Illinois (Ross Adams, Chautauqua National Wildlife Refuge, Havana, Illinois, personal communication).

On the upper Mississippi, four small-scale drawdown projects have been conducted in the past few years. Although the amount of floodplain surface affected by these drawdowns is small relative to the total floodplain, these pilot experiments are designed to show whether drawdowns of an entire navigation reach would provide sufficient ecological benefits to outweigh temporary constraints on commercial navigation and recreational boating. In 1996 and 1997, Wisconsin and Minnesota funded, implemented, and monitored two local drawdowns along the upper Mississippi River that increased the abundance and diversity of emergent aquatic plants. But these drawdowns also revealed several logistical problems that must be anticipated in similar projects: maintenance of pumps that may have to run intermittently for many weeks, rain, seepage through levees, groundwater inflows, and muskrat burrows that damage levees. An additional small-scale drawdown project, located in Reach 5, took place in the summer of 1997. The site was selected in part because of its public visibility, and the drawdown was used as an educational opportunity as well as for its experimental value.

Using navigation dams to naturalize flood regimes. Navigation dams affect water levels over much larger areas than small-scale drawdowns. At the request of the Missouri Department of Conservation, the St. Louis District of the US Army Corps of Engineers experimented with an altered regulation strategy starting in 1994 in navigation reaches 24–26 (Wlosinski and Hill 1995, Wlosinski and Rogala 1996). Missouri's initial request was to hold the water in Reach 25 at 0.15 meter lower than the maximum regulated level for a period of 20 days (Busse et al. 1995). The Corps determined that this request could be satisfied while still maintaining the minimum navigation depth of 2.7 m. The drawdowns, which were done in reaches 24, 25, and 26, resulted in abundant growth of emergent vegetation over a total of approximately 202–243 ha of mudflats, which would ordinarily have remained shallow, muddy, and without rooted vegetation.

Other districts of the Corps are now planning experimental drawdowns. The St. Paul District analyzed the probable effects on vegetation and recreational use of drawdowns of different magnitudes and at different river discharges in Reach 8 (WLMTF 1996), and a public information and education campaign is under way to explain the purpose and likely outcomes. As these experiments indicate, both state and federal natural resource management agencies understand that variation in water levels maintains the structure and function of river–floodplain ecosystems, and managers are beginning to think at scales beyond moist-soil compartments or even single wildlife refuges.

Conclusions and recommendations

Large rivers and their floodplains are used for many purposes and cannot be wholly protected within parks and reserves. Some would argue that restoration (approximating a condition prior to human alteration) is not even a viable policy option for large-river systems. So how is it possible to move beyond improvement of fish and wildlife habitat in selected areas to the broader and more elusive goals of ecosystem management and restoration, which require managed and/or natural floods (NRC 1992, Poff et al. 1997)? After a century of draining wetlands for agriculture, preventing floods with levees, and maintaining water levels for navigation with dams, relaxation of constraints on both high and low water levels is a radical idea.

Managed flooding usually involves re-creating seasonal flooding patterns to benefit flood-adapted plants and animals or to restore flood-dependent geomorphic features, such as riparian beaches valued by humans (see Schmidt et al. 1998). In the Illinois and upper Mississippi Rivers, management also involves prevention of flooding: Low levees are used to exclude unnatural small floods that occur during the summer growing season. Gates in the low levees allow the river to enter in the fall to benefit migrating waterfowl—if the river does not oblige, pumps are used to create the fall flood.

It would, however, be prohibitively expensive to adopt the same techniques (levees, gates, and pumps) to manage the spring flood to restore slower, more natural rates of rise and recession. The spring flood typically rises higher than the fall flood, so expensive, high levees would be required to control it. In addition, existing flood-protection levees elsewhere would have to be raised to compensate for increased flood heights caused by the new levees, which would reduce flood storage and conveyance capacity on the floodplain. Although new high levees are not likely to be built, several existing levee districts with high levees have been acquired from willing sellers by conservation organizations and by state and federal natural resource agencies. (A levee district is an administrative unit consisting of the lands enclosed within a system of levees. Districts have legal authority to tax landowners to maintain the levees and internal drainage systems and to pay pumping costs.)

There are contrasting views about the maintenance and operation of both low and high levees. Some resource managers feel that reconnecting rivers and their floodplains should be considered only if unnatural fluctuations in river flow and unnatural loads of sediment, nutrients, and contaminants in the rivers are reduced to levels that existed before European settlement; otherwise, the floodplain wetlands will be irretrievably degraded. They further argue that because that level of reduction will never occur so long as most of the watershed is used for agriculture and boats resuspend sediments in the main channel, reconnection is not a feasible option, now or in the foreseeable future. Therefore, the high levees should be maintained to keep polluted and sediment-laden river water out of floodplain wetlands altogether, and the low levees should be used to exclude the unnatural small summer floods. However, we do not believe the situation is so hopeless and offer several alternatives to isolating the floodplain from the river.

Adopt an ecosystem perspective. An ecosystem perspective can reveal opportunities to restore ecosystem structure and function that might be overlooked by traditional natural resource management and engineering approaches. Engineering focuses on controlling the natural resource to provide for a particular human use. Control, risk minimization, and consistency (e.g., consistent water supply) are important objectives. Some resource managers may be production specialists, who seek to maintain or enhance production of particular renewable resources (wildlife, fish, and timber) for commercial or recreational uses.

By contrast, the systems ecologist and geologist seek to understand the natural system and its history, rather than focusing at first on practical human use. Some people often wonder why such information is even relevant, beyond hydrological records that can be used to establish design criteria for levees. The past is relevant because restoration or naturalization involves returning an ecosystem to some approximation of a historical or prehistorical reference condition. Some people see this objective as regression, rather than progress, and some resource managers regard it as either impossible, because they believe the natural system is irretrievably altered, or undesirable, if the altered system yields more fish, game, or timber per acre. However, if the social goal really includes restoration, rather than just a consistent yield of consumable products, and if there are no unaltered contemporary rivers for comparison, then the past furnishes a guide for design and a standard for performance.

Another persuasive argument for adopting an ecosystem perspective and investigating the past is that by understanding how the natural system worked we better understand not only what needs to be done now, but also how to do it in a cost-effective way. The system sciences of ecology and geology identify the master variables that control the ecosystem (e.g., the water and sediment regimes in rivers) and describe cause–effect pathways. Once these pathways are described quantitatively, predictions can be made about the effects of alternative management scenarios, including long-term systemic effects. Such analyses may reveal new, cost-effective approaches, even in cases in which management objectives are species specific (i.e., they enhance habitat for a particular species or group of species). A general principle of systems is that relatively small expenditures of energy applied through appropriate controls can cause disproportionately large shifts in energy fluxes or other processes. For example, a river expends huge quantities of energy moving water and sediments, but only a relatively small amount of energy is needed to place rocks in such a way that the river will subsequently deposit sediments and build an island downstream of the rocks. The island can serve as a breakwater that shelters submerged aquatic plants from waves. Eventually, trees can grow on the island, increasing its effectiveness as a windbreak. It is cheaper to "grow" an island in this way than it is to build one entirely by dredging up sediment.

An ecosystem perspective is also useful in understanding patterns in contemporary, altered rivers and devising more effective management techniques. For example, the effect of dam operations on the water-level regime can be put to good use in selecting sites for preserves. Dams stabilize water levels during the summer low flow at some locations within the reaches between dams, and they destabilize or even invert the natural pattern elsewhere (Figure 7; Sparks 1995). A moist-soil management unit for waterfowl should therefore be located where the water levels are stabilized and small summer floods are unlikely to occur. It might even be possible to use navigation dams to manage the water levels for moist-soil plant production over a larger portion of the river reach. In contrast to sedges and other moist-soil plants, bottomland hardwoods should be restored well upstream of the influence of the dams, where water levels drop sufficiently to provide the greater unsaturated soil depth needed by these trees (Figure 6). It would be more expensive to build up the land elevation for forest restoration by dredging or hauling in soil. It also would be more expensive to locate a moist-soil management unit where higher levees and bigger pumps are needed to counteract the water-level fluctuations caused by the dams.

Define the problem and the scale. An ecosystem perspective can help to separate symptoms from causes and reveal the larger and longer-term situation in which preserves and refuges are embedded. If low levees and pumps are necessary to exclude unnatural small floods and to re-create the fall flood, it is important to ask what causes the small floods and what can be done at the system level to reduce them. If the operation of the navigation dams causes the summer spikes (as seems to be the case; Figure 7), then modifying the operation of the dams is far cheaper than building more leveed compartments on the floodplain and operating gates and pumps. However, if upland drainage and channelization of tributaries create the small floods in the main river by speeding runoff downstream, then water retention capacity in the watershed should be increased, slowing the water flow. Creation or restoration of wetlands in the watershed and dechannelization of tributaries might cost more than building leveed compartments on the floodplain of the main river, but the wetlands and dechannelizations would also reduce the loads of sediment, nutrients, and contaminants carried down tributaries to the main river. Another possibility is to operate the navigation dams to actively counteract small floods delivered by tributaries, instead of merely avoiding dam operations that create fluctuations. Such active management could dampen water fluctuations immediately, whereas watershed and tributary treatment will take decades.

An even more fundamental question than the source of the small floods is whether the contemporary water regime or the sediment regime is the greatest stress on the floodplain–river ecosystems. The best answer for now is that both need to be addressed, but the question merits more analysis; otherwise, too much may be spent on reducing one stress and not enough on the other. It is important to determine how much of the sediment is eroded from the beds and banks of the tributary rivers as a result of delivering more storm water at unnaturally fast rates from both urban and agricultural areas. The unnatural water regime contributes to the unnaturally high rates of channel erosion in tributaries and sedimentation in backwaters of the mainstem rivers. Traditional soil conservation measures are unlikely to ameliorate this water management problem.

Although the detrimental effects of excessive sediment on aquatic ecosystems are well documented, both the public and policymakers need to understand that erosion and sedimentation are natural processes in alluvial rivers and that many of the attractive natural features of the Illinois and upper Mississippi Rivers are products of sedimentation. For example, Lake Pepin on the upper Mississippi and the lakes at Peoria on the Illinois River are natural lakes (although lake levels are now higher because of navigation dams) created by tributary deltas that dammed the main rivers. Although the deltas appear to be static, they were and are in a dynamic equilibrium, with sediment delivery by the tributary balancing sediment transport by the main river. Some degree of sedimentation is useful because it can be harnessed to create and maintain desirable features, such as the islands mentioned above or natural levees where native pin oaks and

Figure 9. The confluence of the Missouri and Mississippi Rivers just upstream of St. Louis during the 1993 flood. The Missouri is left of center, with the banks delineated by trees; the Mississippi is to the right, with commercial barges tied to the banks. The levee held in Wood River, IL (the city in the foreground). Lock and Dam 26 is just downstream of the bridges visible in the middle distance on the Mississippi at Alton, IL. The lock and gates are visible, but the dam is completely submerged. Some of the water from the Missouri took a shortcut across St. Charles County, MO, into the Mississippi upstream of Dam 26. Photo: Surdex, Inc., St. Louis.

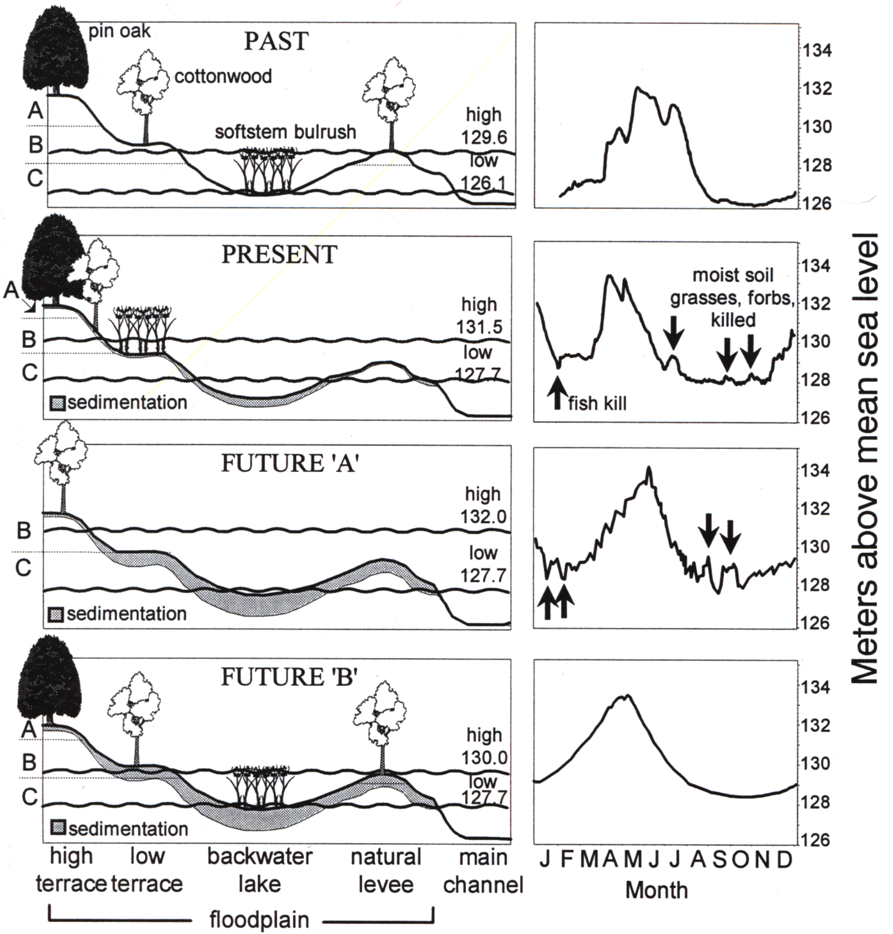

Figure 10. Plant diversity and productivity on floodplains are regulated by flood frequency, timing, and duration, which are determined by land elevation (diagrams at left) and flood regime (hydrographs at right). Zones A, B, and C are at progressively lower land elevations and support plant communities represented by pin oak (*Quercus palustris*), cottonwood (*Populus deltoides*), and softstem bulrush (*Scirpus validus*), respectively. In the past (1892 hydrograph, Illinois River mile 43), all zones were represented in the floodplain, and the low, stable water levels of midsummer allowed forbs and grasses to grow on moist soils and submersed aquatic vegetation to grow in permanent lakes. At present (1983 hydrograph), the low water elevation has been permanently raised 1.6 m by navigation dams and water diversion, flood peaks are higher, and small-scale fluctuations are more frequent. Relatively small water level drops in winter kill fish, and small rises in summer drown moist-soil plants. The pin oak community survives only on the remaining highest terraces. If current trends continue (Future 'A'), then flood heights and short-term fluctuations will increase, eliminating Zone A. Sedimentation will raise the floodplain, but excessive water-level fluctuations will inhibit most native plants. If steps described in the text are taken to smooth the hydrograph (Future 'B'), then all three zones and their associated native plant communities could recover. The smoothed hydrograph would be superimposed on a higher base water level (maintained by the navigation dams), but sedimentation would raise the floodplain elevation so that the topography and plant communities would come to closely resemble those of the past (1892).

pecans can grow.

Simply reducing sediment loads without naturalizing the water regime will not maintain or restore plant communities and the animal populations that depend on them (Figure 10). The water regime may be even more critical in terms of plant biodiversity: If the water regime is naturalized and summer floods are reduced, mudflats that are exposed during low flows can be colonized by moist-soil plants (including the decurrent false aster, which is federally listed as threatened). If the water regime is naturalized only within isolated compartments on the floodplain, then the moist-soil plant community is maintained but migratory fishes have difficulty getting in and out. An ecosystem perspective and a fundamental understanding of the hydrology of floodplains can help to resolve this dilemma because it is possible to use natural mechanisms that once protected the floodplain lakes from excessive sedimentation to keep sediments out while fish are let in.

Use natural protective mechanisms. Simply looking at pre-1900 maps of the Illinois and upper Mississippi Rivers reveals much about the design and functioning of the predam rivers that could be applied to river restoration today. First, backwaters and floodplain lakes were much smaller during the low-flow season than they are today (because the navigation dams do not allow the river to drop as low as it did naturally), so that winds did not blow over large expanses of water and build large waves that resuspended sediments. Because the permanent aquatic areas were much smaller, more of the floodplain was occupied by trees and other terrestrial plants that served as windbreaks and anchored the soil during spring floods. Therefore, even though the water surface area expanded during the flood, waves were not as severe a problem as they are now.

Second, many of the permanent aquatic areas on the floodplain were connected to the river by only a sinuous channel that passed out the downstream end through marshes into the river. Other aquatic areas were relatively far from the river, close to the river bluffs, and had no direct connections to the river during low flow. The river did not pour suddenly into either of these two types of aquatic areas during typical spring floods, nor did it run through them from upstream to downstream. Rather, the river backed up slowly into the water bodies (which explains why they are called "backwaters"), passing through channels and wetlands that tended to trap sediments. Not only were sediments removed by filtering and settling, but also the sands carried along on the bottom of the main river channel (the bed load) did not enter the backwaters because the water was effectively decanted off the top of the water column. In other areas, such as side channels, a portion of the river flow did pass through from upstream to downstream, but many of these channels were also self-scouring.

Third, many of the wetlands and lakes filled with clear water before the river ever got to them (Kofoid 1903). The same phenomenon occurs today in five of the six large floodplain–river ecosystems investigated by Mertes (1997), including the upper Mississippi. In the rain or snowmelt seasons, backwaters and lakes on the floodplain start filling with water from a variety of sources: rainwater that falls directly on the lakes, overland runoff from the highlands and local watersheds, tributary water, and rising groundwater. The quality of the water depends on its source: Lakes with silty tributary inflows are not as clear as lakes that fill with groundwater and rain. Once these areas fill with relatively clear water, it is difficult for silty water to enter from the river. The process is rather like trying to put more water into a bottle that is already full. It is no problem, however, for fish to swim through the so-called perirheic zone (*sensu* Mertes 1997)—that is, the mixing zone where river water meets local floodplain water.

Thus, historical investigation and contemporary comparisons of large floodplain–river ecosystems both suggest that rivers could be reconnected to their floodplains without degrading wetlands and permanent aquatic areas if the areas prefilled with clear water and the river backed in slowly through filtering wetlands. But in this case, again, the water regime is paramount: If the river rises too high and too fast, filtering and hydraulic damming may not occur. If the flow regime in the river cannot be naturalized before the floodplains are restored, it will probably be necessary to retain some control over the flooding pattern in floodplain compartments. The high levees around levee districts that are acquired for restoration should be left in place, but gates should be installed so that when the interior water level approaches that of the river, fishes can move freely in while most of the sediment is kept out. During recession of the flood, the gates can be used to prolong the flood and lower the water level slowly inside the levee district, allowing adult fish to spawn and their young to grow.

The gates could also be used to protect the levees from great floods at far less cost and risk of failure than heroic emergency measures, such as sandbagging. The major damage to levees during great floods occurs when the levees are overtopped or breach and the water rushes in, creating a scour hole and carrying earth from the collapsing levee well into the levee district. Gates can be used to equalize the water levels on both sides of the levee as the flood crests. Even if the levee were to go under water, there would be far less damage because there would be less scouring. Moreover, a levee district used in this way can help to take the crest off a flood, reducing damage elsewhere. Finally, gate-equipped levee districts that are no longer used for agriculture would be ideal places to conduct manipulative experiments, to design and test the protective mechanisms described above, and to quantify relationships between water regimes and the structure and function of floodplain ecosystems, thereby improving both the science and practice of floodplain–river restoration.

Manage adaptively. Adaptive management is an essential component of ecosystem management and something that all natural resource managers should be doing: That is, they should adjust their management seasonally or annually to the current environmental and biological conditions and in response to new social values and new scientific information and knowledge. Adaptive management recognizes that the structure and function of natural and restored systems vary across space and time; indeed, that *variation* (disturbance regime) is *required* to maintain many ecosystems. Planning and engineering to incorporate this variability requires change on the part of management agencies, whose historic missions have generally involved reducing variability (in such things as water supply, channel positions of rivers, and supply of fish and game).

The general principle of adaptive management is to let nature "have a say" in setting the management schedule and annual objectives. Adaptive management does not mean "hands-off" or no management, but it does mean "going with the flow" and making adjustments, rather than adhering to a rigid practice or schedule. These annual adjustments are best done in the context of a strategic plan that includes contingencies. For example, if a given year turns out to be a drought year, then it might be a good time to let backwaters along a river dry out and sediments compact, rather than erecting temporary dikes to maintain water levels. Compacted sediments are less prone to resuspension by wave action when reflooded and, consequently, provide better substrate for wetland plants and animals. A drought year also might be a good time to establish trees on the floodplain, such as bald cypress (*Taxodium distichum*). Cypress seeds will not germinate in water, even though the saplings and mature trees are flood tolerant. At the other extreme, a year with a protracted major spring flood might be a good year to manage a low-lying floodplain area for fish recruitment instead of production of moist-soil food plants for waterfowl.

Adaptive management is predicated on the resistance and resilience of species and ecosystems to a natural range of variation and on the preservation of a sufficiently large area that most species' habitat requirements will be met somewhere, if not on the same site every year. Adaptive management is also based on the recognition that maximum diversity is often associated with an intermediate level of variation in environmental factors (the Intermediate Disturbance Hypothesis; Connell 1978) and that some ecosystems and species are maintained by disturbance regimes. For example, floodplain vegetation is maintained by moderate seasonal floods and occasional great floods and droughts (Sparks 1996). There are exceptions to the general principle of allowing a natural range of variation to occur, of course. For example, a threatened species that occurs in only a very restricted location can be exterminated by a disturbance.

When implementing adaptive management in the context of floods, there should be decision thresholds: Once a flood lasts beyond a date that is optimum for moist-soil plant production, then management of the refuge should shift to the fish-recruitment objective. The same floodplain area might be used to take the crest off a record flood that threatens a city. In this case, hydraulic services (flood conveyance) would occasionally take precedence over all other management services, although it certainly would be possible to add some environmental benefits (e.g., fish recruitment) to flood conveyance.

Capitalize on natural experiments. Large, infrequent disturbances, such as record floods, are special cases that should be regarded as natural experiments. Plans should be made in advance to provide the extra expertise and effort from the state, regional, or national levels to assist sites that experience a great flood, drought, or other major, infrequent disturbance. Management and sampling objectives should be adjusted in response to the event, so as to document and quantify both the event itself and its ecological effects. Resources must be allocated to follow the recovery and adjustment process. Off-site effects of the disturbance might be documented as well, to answer stakeholders' questions about beneficial and detrimental effects of natural and restored sites. Stakeholders are often worried about the effects of the site under extreme conditions, not under average or typical conditions. For example, riparian zones that have been revegetated with native riparian plants that stabilize banks and retard flood flows can back up water during a major flood, in comparison to a denuded or revetted bank. Downstream stakeholders might be pleased that flood crests are reduced and desynchronized, but upstream stakeholders might be fearful that water will be backed up onto their property to a greater degree than would have occurred with the channelized stream and denuded riparian zone.

Conduct management experiments. Adaptive management goes beyond opportunism, however. Site management should promote both the science and practice of environmental engineering and ecological restoration through experimentation. A scientifically based management experiment is not at all "trial and error." A management experiment begins with the best available knowledge and develops questions to be answered or hypotheses to be tested. In other words, there is some conception of how things might turn out, but there is also a degree of uncertainty. If the condition of the site prior to degradation is known, the prior condition can be used as the management goal or target for restoration. It is always useful to develop a conceptual model (consisting of simple diagrams and descriptions) of how the ecosystem works, and it may be worthwhile to go one step further, to a simulation model. Both types of models will help to identify information gaps and guide planning and sampling design. The master variables (e.g., the water regime) that strongly influence the site should be identified and measured for the purpose of quantifying cause–effect relationships. Key indicators (species or communities) should be identified and their expected responses described.

Experimentation does pose some risk, so initial experiments might be done on small areas. If the question can be answered only by utilizing a large site, then it should be designed so corrective action can be taken if early warning signs appear that the experiment is harming the site. If, on the other hand, early results are encouraging, the treatment can be continued or even expanded.

Monitor and assess. Management cannot be adaptive without information about the current status and trends in the key driving variables (e.g., the sediment and water regimes) and the indicators of interest (e.g., the population status of key species). A management experiment is worthless without data to show whether the hypotheses were rejected or accepted. Failure is instructive, so long as sufficient information has been gathered to understand *why* the failure occurred. Similarly, little is gained by success if the reasons for success are not known; it may be impossible to extend the results to another site, or even to repeat them at the same site. Worse, there may be little confidence that the success was triggered by the management practice and not by some natural change that was unaccounted for.

Use the expertise of fluvial geologists, systems ecologists, economists, and sociologists. The longer-term and larger-scale perspectives of the fluvial geologist and systems ecologist are essential to understanding how large floodplain rivers work, what successional changes are occurring, and what restorative actions are likely to be effective (White 1977, Petts 1984). Economists and sociologists also have important roles because they investigate what people value, what ways to achieve those values are acceptable, and how conflicts and contradictions can be resolved. Achieving restoration objectives involves social consent to some release of constraints to achieve a natural range of variability. Although stabilized rivers and reservoirs provide many human services, including water supply and outdoor recreation, maintenance of a functioning floodplain–river ecosystem and its full complement of species requires some degree of floodplain–river connectivity, seasonal flooding, and topographic diversity (Heiler et al. 1995, Lubinski 1995, Ward and Stanford 1995). Determining just how much, when, and where is both a key area of research in floodplain–river ecology and a focus of public debate.

Acknowledgments

The Long Term Resource Monitoring Program, a component of the cooperative federal–state Environmental Management Program for the Upper Mississippi River System (which includes the Illinois River), generated much of the information discussed in this article. We are grateful to the cooperating agencies—the US Army Corps of Engineers (St. Paul, Rock Island, and St. Louis Districts), the US Fish and Wildlife Service, the Biological Resources Division of the US Geological Survey, and the state natural resource agencies of Minnesota, Wisconsin, Iowa, Illinois, and Missouri. A short grant for exploratory research from the National Science Foundation (DEB-9524436) supported an investigation of vegetation and nutrient dynamics on the floodplains following the 1993 flood. Grant no. DEB-9613562 under the NSF/Environmental Protection Agency Partnership for Environmental Research currently supports Richard Sparks and his colleagues at the University of Illinois, who are analyzing the hydrological, ecological, and economic effects of alternative floodplain management and dam operation strategies. We thank Douglas Blodgett, Thad Cook, Kevin Irons, Paul Raibley, and Ted Snider for figures; Penelope Firth, Seth Reice, Ruth Sparks, an anonymous reviewer, and the editor for improvements to the text; and Camilla Smith for checking literature citations. The opinions expressed in this article are those of the authors and not necessarily their agencies.

References cited

Akanbi A, Singh KP. 1997. Managed flood storage option for selected levees along the lower Illinois River for enhancing flood protection, agriculture, wetlands, and recreation. Second report: Validation of the UNET model for the lower Illinois River. Champaign (IL): Illinois State Water Survey, Hydrology Division. Contract Report no. 608.

Bartels AD. 1995. Growth of selected fishes in Navigation Pool 8 of the upper Mississippi River: A test of the flood-pulse concept. Master's thesis. University of Wisconsin–La Crosse, La Crosse, WI.

Bayley PB. 1995. Understanding large river–floodplain ecosystems. BioScience 45: 153–158.

Belt CB Jr. 1975. The 1973 flood and man's constriction of the Mississippi River. Science 189: 681–684.

Busse D, Dalrymple K, Strauser CN. 1995. Environmental pool management. Pages 55–65 in Proceedings of the Fifty-first Annual Meeting of the Upper Mississippi River Conservation Committee. Rock Island (IL): Upper Mississippi River Conservation Committee.

Carlson B. 1993. Economic impacts of recreation, Upper Mississippi River System. St. Paul (MN): US Army Corps of Engineers, St. Paul District.

Cohen NH, Bartlett SP, Lenke A. 1899. Report of the Illinois state fish commissioner from October 1, 1896, to September 30, 1898. Springfield (IL): Phillips Brothers State Printers.

Connell JH. 1978. Diversity in tropical rain forests and coral reefs. Science 199: 1302–1309.

Dawson FH, Charlton FG. 1988. Bibliography on the hydraulic resistance or roughness of vegetated watercourses. Ambleside, Cumbria (UK): The Freshwater Biological Association. Occasional Publication no. 25.

Delaney RL, Craig MR. 1997. Longitudinal changes in Mississippi River floodplain structure. Onalaska (WI): US Geological Survey. Project Status Report no. PSR 97-02. Upper Mississippi River Long Term Resource Monitoring Program.

Forbes SA, Richardson RE. 1920. The Fishes of Illinois. 2nd ed. Champaign (IL): Illinois Natural History Survey.

Fredrickson LH, Taylor TS. 1982. Management of seasonally flooded impoundments for wildlife. Washington (DC): US Department of Interior, Fish and Wildlife Service. Resource Publication no. 148.

Heiler G, Hein T, Schiemer F, Bornette G. 1995. Hydrological connectivity and flood pulses as the central aspects for the integrity of a river–floodplain system. Regulated Rivers: Research and Management 11: 351–361.

Hoops R. No date. A river of grain: The evolution of commercial navigation on the upper Mississippi River. Madison (WI): The Research Division of the College of Agricultural and Life Sciences, University of Wisconsin–Madison. University of Wisconsin–Madison College of Agricultural and Life Sciences Research Report no. R3584.

Hutchison GE. 1951. Copepodology for the ornithologist. Ecology 52: 571–577.

Knox JC. 1985. Responses of floods to Holocene climatic change in the Upper Mississippi Valley. Quaternary Research 23: 287–300.

Kofoid CA. 1903. Plankton studies. IV. The plankton of the Illinois River, 1894–1899, with introductory notes upon the hydrography of the Illinois River and its basin. Part I. Quantitative investigations and general results. Illinois State Laboratory of Natural History Bulletin 6: 95–635.

Leopold LB. 1994. Flood hydrology and the floodplain. Pages 11–14 in White GF, Myers MF, eds. Water resources update. Coping with the flood: The next phase. Carbondale (IL): The University Council on Water Resources. Issue no. 94–95.

Lubinski KS. 1995. Bridging the gap between theory and practice on the upper Mississippi River. Regulated Rivers: Research and Management 11: 137–138.

Maher RJ. 1994. Observations of fish community structure and reproductive success in flooded terrestrial areas during an extreme flood on the lower Illinois River. Pages 95–115 in National Biological Service, Illinois Natural History Survey, Iowa Department of Natural Resources and Wisconsin Department of Natural Resources. Long-Term Resource Monitoring Program 1993 Flood Observations. Onalaska (WI): National Biological Service, Environmental Management Technical Center. Report no. LTRMP 94-S011.

Maser C, Sedell JR. 1994. From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans. Delray Beach (FL): St. Lucie Press.

Mertes LAK. 1997. Documentation and significance of the perirheic zone on inundated floodplains. Water Resources Research 33:1749–1762.

Miller AC, Payne BS. 1998. Effects of disturbances on large-river mussel assemblages. Regulated Rivers: Research and Management 14: 179–190.

Mills HB, Starrett WC, Bellrose FC. 1966. Man's effect on the fish and wildlife of the Illinois River. Champaign (IL): Illinois Natural History Survey. Biological Notes no. 57.

[NRC] National Research Council. 1992. Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy. Washington (DC): National Academy Press.

Nelson JC, Sparks RE. 1998. Forest compositional change at the confluence of the Illinois and Mississippi Rivers. Transactions of the Illinois State Academy of Science 91: 33–46.

Nelson JC, Redmond A, Sparks RE. 1994. Impacts of settlement on floodplain vegetation at the confluence of the Illinois and Mississippi rivers. Transactions of the Illinois State Academy of Science 87: 117–133.

Nelson JC, Arndt L, Rushser J, Robinson L. 1996. Presettlement and contemporary vegetation patterns along upper Mississippi River Reaches 25 and 26. Land Use History of North America (LUHNA). Biological Resources Division, US Geological Survey. <http://www.nbs.gov/luhna/emtc/index.html>. 29 Sept. 1997.

Parrett C, Melcher NB, James RW Jr. 1993. Flood discharges in the upper Mississippi River basin, 1993. Washington (DC): US Government Printing Office. US Geological Survey Circular no. 1120-A.

Petts GE. 1984. Impounded Rivers: Perspectives for Ecological Management. John Wiley & Sons.

Pflieger WL. 1975. The Fishes of Missouri. Jefferson City (MO): Missouri Department of Conservation.

Pitlo RH, Dawson FH. 1990. Flow-resistance of aquatic weeds. Pages 74–84 in Pieterse AH, Murphy KJ, eds. Aquatic Weeds: The Ecology and Management of Nuisance Aquatic Vegetation. New York: Oxford University Press.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. BioScience 47: 769–784.

Rabalais NN, Turner RE, Wiseman WJ Jr., Dortch Q. 1998. Consequences of the 1993 Mississippi River flood in the Gulf of Mexico. Regulated Rivers: Research and Management 14: 161–177.

Raibley PT, Sparks RE. 1997. River levels and largemouth bass populations in the Illinois River. Champaign (IL): Illinois Natural History Survey. Report no. 344.

Rhoads BL, Herricks EE. 1996. Human-induced change in low-energy agricultural streams: An example from east-central Illinois. Pages 968–973 in Brookes A, Shields FD Jr., eds. River Channel Restoration. Chichester (UK): Wiley.

Scarpino PV. 1985. Great River: An Environmental History of the Upper Mississippi, 1890–1950. Columbia (MO): University of Missouri Press.

Schmidt JC, Webb RH, Valdez RA, Marzolf GR, Stevens LE. 1998. Science and values in river restoration in the Grand Canyon. BioScience 48: 735–747.

Singh KP, Ramamurthy SR. 1990. Climate change and resulting hydrologic response: Illinois River basin. Pages 28–37 in Riggins RE, ed. Watershed planning and analysis in action: Symposium proceedings of Illinois River conference on watershed management. New York: American Society of Civil Engineers.

Smith M, Keevin T, Mettler-McClure P, Barkau R. 1998. Effect of the flood of 1993 on *Boltonia decurrens*, a rare floodplain plant. Regulated Rivers: Research and

Management 14: 191–202.

Southard R. 1995. Flood volumes in the Upper Mississippi River basin, April 1 through September 30, 1993. Washington (DC): US Government Printing Office. US Geological Survey Circular no. 1120-H.

Sparks RE. 1995. Need for ecosystem management of large rivers and their floodplains. BioScience 45: 168–182.

______. 1996. Ecosystem effects: Positive and negative outcomes. Pages 132–162 in Changnon SA, ed. The Great Flood of 1993: Causes, Impacts, and Responses. Boulder (CO): Westview Press.

Sparks RE, Spink AJ. 1998. Disturbance, succession, and ecosystem processes in rivers and estuaries: Effects of extreme hydrologic events. Regulated Rivers: Research and Management 14: 155–159.

Spink AJ, Rogers S. 1996 The effects of a record flood on the aquatic vegetation of the upper Mississippi River system: Some preliminary findings. Hydrobiologia 340: 51–57.

Spink AJ, Sparks RE, van Oorshot M, Verhoeven J. 1998. Nutrient dynamics of large river floodplains. Regulated Rivers: Research and Management 14: 203–216.

Thiel PA, Fritz AW. 1993. Mussel harvest and regulations in the Upper Mississippi River System. Pages 11–18 in Cummings KS, Buchanan AC, Koch LM, eds. Conservation and Management of Freshwater River Mussels. Proceedings of the Upper Mississippi River Conservation Committee [UMRCC] Symposium; 12–14 Oct 1992; St. Louis, MO. Rock Island (IL): UMRCC.

Theiling CH. 1995. Habitat rehabilitation on the upper Mississippi River. Regulated Rivers: Research and Management 11: 227–238.

Thompson J. 1989. Case studies in drainage and levee district formation and development on the floodplain of the lower Illinois River, 1890s to 1930s. Urbana (IL): Water Resources Center. Special Report no. 016.

[UMRBC] Upper Mississippi River Basin Commission. 1981. Comprehensive master plan for the management of the Upper Mississippi River System. Minneapolis (MN): UMRBC.

[UMRCC] Upper Mississippi River Conservation Committee. 1992. Upper Mississippi River commercial fisheries statistics for 1990. Pages 151–156 in Proceedings of the Forty-eighth Annual Meeting of the UMRCC. Rock Island (IL): UMRCC.

______. 1993. Upper Mississippi River commercial fisheries statistics for 1991. Pages 140–145 in Proceedings of the Forty-ninth Annual Meeting of the UMRCC. Rock Island (IL): UMRCC.

______. 1994. Upper Mississippi River commercial fisheries statistics for 1992 and 1993. Pages 112–125 in Proceedings of the Fiftieth Annual Meeting of the UMRCC. Rock Island (IL): UMRCC.

______. 1995. Upper Mississippi River commercial fisheries statistics for 1994. Pages 94–98 in Proceedings of the Fifty-first Annual Meeting of the UMRCC. Rock Island (IL): UMRCC.

[USACE] US Army Corps of Engineers. 1997. Report to Congress: An evaluation of the Upper Mississippi River System Environmental Management Program. Rock Island (IL): USACE, Rock Island District.

Ward JV, Stanford JA. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research and Management 11: 105–119.

[WLMTF] Water Level Management Task Force. 1996. Problem appraisal report for water level management, Pool 8, upper Mississippi River. St. Paul (MN): US Army Corps of Engineers, St. Paul District.

White GF. 1977. Comparative analysis of complex river development. Pages 1–21 in White GF, ed. Environmental Effects of Complex River Development. Boulder (CO): Westview.

Williamson R. 1996. 1995 commercial catch report exclusive of Lake Michigan. Springfield (IL): Illinois Department of Natural Resources.

Wlosinski JH, Hill L. 1995. Analysis of water level management on the upper Mississippi River (1980–1990). Regulated Rivers: Research and Management 11: 238–248.

Wlosinski JH, Rogala J. 1996. Pool 25: Water level management alternatives and their effects on habitat. Onalaska (WI): National Biological Service, Environmental Management Technical Center. Report no. LTRMP 96-T004.

Yeager LED. 1949. Effect of permanent flooding in a river bottom timber area. Illinois Natural History Survey Bulletin 25(2): 33–65.

Yin Y. 1998. Flooding and forest succession in a modified stretch along the Upper Mississippi River. Regulated Rivers: Research and Management 14: 217–225.

Yin Y, Nelson J. 1996. Modifications of the Upper Mississippi River and the effects on floodplain forests. Pages 29–40 in Galat DL, Frazier AG, eds. Overview of River-Floodplain Ecology in the Upper Mississippi River Basin. Vol. 3 of Kelmelis JA. Science for Floodplain Management into the 21st Century. Washington (DC): US Government Printing Office.

Yin Y, Nelson J, Stenson GO, Langrehr HA, Blackburn TA. 1994. Tree mortality in the upper Mississippi River and floodplain following an extreme flood in 1993. Pages 39–60 in National Biological Service, Illinois Natural History Survey, Iowa Department of Natural Resources, and Wisconsin Department of Natural Resources. Long-Term Resource Monitoring Program 1993 Flood Observations. Onalaska (WI): National Biological Service, Environmental Management Technical Center. LTRMP 94-S011.

Yin Y, Nelson J, Lubinski KS. 1997. Bottomland hardwood forests along the Upper Mississippi River. Natural Areas Journal 17: 164–173.