Need for Ecosystem Management of Large Rivers and Their Floodplains

These phenomenally productive ecosystems produce fish and wildlife and preserve species

Richard E. Sparks

Most of the 79 large river–floodplain ecosystems in the world have been altered by human activities; the rest are likely to be altered soon (Welcomme 1985). These complex ecosystems are composed of the flowing channels that most people associate with rivers, together with the floodplain lakes, backwaters, forests, and wetlands that harbor much of Earth's terrestrial and freshwater biodiversity (Figures 1–3). River-floodplain ecosystems, unlike most lakes, are characterized by seasonal floods that promote the exchange of nutrients and organisms among a mosaic of habitats and thus enhance biological productivity (Bayley page 153 this issue, Junk et al. 1989).

Annual flood pulses are so predictable and long-lasting that plants, animals, and even human societies have adapted to take advantage of them. In ancient Egypt and Mesopotamia, the fertility of the soils was renewed each year by the annual overflow of the rivers, thereby sustaining large populations in one place for millennia and permitting the development of great civilizations. Outside these floodplains, the fertility was exhausted by a few years of steady cultivation, so people had to move on.

Richard E. Sparks is director of the River Research Laboratory, P. O. Box 590, Havana, IL 62644, a unit of the Center for Aquatic Ecology, Illinois Natural History Survey.

Ecosystem management works to guide, rather than thwart, natural processes

Despite centuries of alteration in the developed world, remnant river-floodplain ecosystems still exist. Central Europe's largest river, the Danube, retains 650 km^2 of its former floodplain in Slovakia and Hungary despite changes caused by dredging, channelization, and dam-building (Bacalbasa-Dobrovici 1989, Pearce 1994).

In the United States, most of the 98,000-square-kilometer floodplain along the Mississippi downstream from the mouth of the Ohio has been leveed and drained for agriculture, but sizable floodplains have been preserved along the upper Mississippi north of St. Louis as part of the National Fish and Wildlife Refuge System (NRC 1992). Two large tributaries of the Mississippi—the Illinois River, and the lower portion of the Missouri River—retain flood pulses and floodplains, and a major distributary (branch) of the Mississippi—the Atchafalaya—is building new deltaic floodplain in the Gulf of Mexico, thereby increasing what is already North America's largest remaining (5700 km^2) river overflow swamp (Hesse et al. 1989, 1993, NRC 1992).

In the developing world, extensive river-floodplain ecosystems remain, but they are diminishing at increasing rates as land use intensifies and as many countries attempt to follow the western model of economic development through the use of massive water resource projects (Sparks 1992). There now are dams on virtually all the large rivers in Africa (Obeng 1981). In South America, the upper Paraná is dammed, but the middle and lower reaches still retain natural floodplains, and the Paraná's largest tributary, the Paraguay, remains free-flowing.[1] Earth's largest river (in terms of flow), the Amazon, remains undammed, but it has been affected by clearing of the upland and floodplain forests. Also, 100 planned tributary dams may block or impede fish migrations (Fearnside 1989, Junk and de Mello 1987).

In 1993 and 1994, international attention was focused on large rivers and their floodplains when disastrous floods occurred in Bangladesh, western Europe, and the United States. Now questions are being asked about the effectiveness and cost of current flood and floodplain management policies and about the potential for reducing future flood damage by preserving and restoring large river–floodplain ecosystems and their tributary watersheds and wetlands (Sklar 1993, Sparks and Sparks 1994).

This focus on flood-damage re-

[1]Edmundo Drago, 1994, personal communication. Instituto Nacional de Limnologia, Santa Fe, Argentina.

duction reinforces interest, which had already been building, in ecosystem management and recovery. Large river–floodplains are unique ecosystems distinct from both small streams and narrow-valley large rivers. The concept that large river–floodplain integrity is maintained by hydrological dynamics (flood pulses) and river-floodplain connectivity are relatively recent ideas (Junk et al. 1989, Welcomme 1979). Although Forbes (1895) and Richardson (1921) in the United States and Antipa (1928) in Hungary and Romania had the temerity to sample large rivers and their associated floodplains and backwaters at the turn of the twentieth century and to recognize the relationship between flood pulses and biological productivity, their work was not followed up on until much later. With the exception of this largely forgotten early research, lotic ecology has focused on smaller streams and rivers, and environmental management agencies have focused on water quality, designing monitoring programs from a largely one-dimensional, channel-oriented perspective (i.e., to assess impacts of point sources of pollution along the lengths of rivers).

In 1977 the US Clean Water Act established a goal of "...restoration of the physical, chemical and biological integrity of the nation's waters...," but the US Environmental Protection Agency subsequently concentrated on the chemical part of this integrity triad (NRC 1992). State and federal environmental agencies used the indices primarily to assess how well pollution-abatement programs were working, even though ecologists developed various indices of biotic integrity and described how other factors such as river flow, type of bed material, food source, and biotic interactions (e.g., disease, parasitism, competition, and predator-prey effects) affect biotic integrity (Karr and Dudley 1981). River flow patterns were of concern primarily in relation to their influence on waste-assimilative capacity (i.e., during low flows there is less dilution of contaminants; NRC 1992). Although water quality is important and necessary to maintain biological integrity, it is not sufficient by itself, particularly in river-floodplain ecosystems where flood pulses are the key driving force.

Figure 1. The confluence of the Illinois River, entering from the bottom, and the upper Mississippi River, entering from the right, 38 river miles upstream of St. Louis. The view is looking downstream. The floodplain forests, lakes, backwaters, and side channels in the foreground are characteristic of the natural rivers. The rectangular farm fields in the upper right are on the Missouri side of the Mississippi. The farms are not protected by levees but are on a naturally elevated portion of the floodplain that rarely floods. The Great River Road, a scenic drive, and limestone bluffs demarcate the Illinois side at the upper left. The width of the Mississippi at the confluence at the top left is approximately 1.6 km.

Figure 2. The bottomland forest of the Sanganois Conservation area, where the Sangamon River joins the Illinois River, near Beardstown, Illinois. The main channel of the Illinois River is at the top left of the picture (the river flows from right to left) and is flanked by a smaller abandoned channel. The forest includes some native pin oaks (*Quercus palustris*) and pecans (*Carya illinoensis*) on natural levees, as well as more common black willow (*Salix nigra*), cottonwood (*Populus deltoides*), elm (*Ulmus americana*), and silver maple (*Acer saccharinum*) in low-lying areas. The distance from the top to the bottom of the picture is approximately 6 km.

In this article, I describe the importance of large river–floodplain ecosystems and some of the consequences of altering their natural processes, functions, and connectivity. Then I contrast the species-focused management typically em-

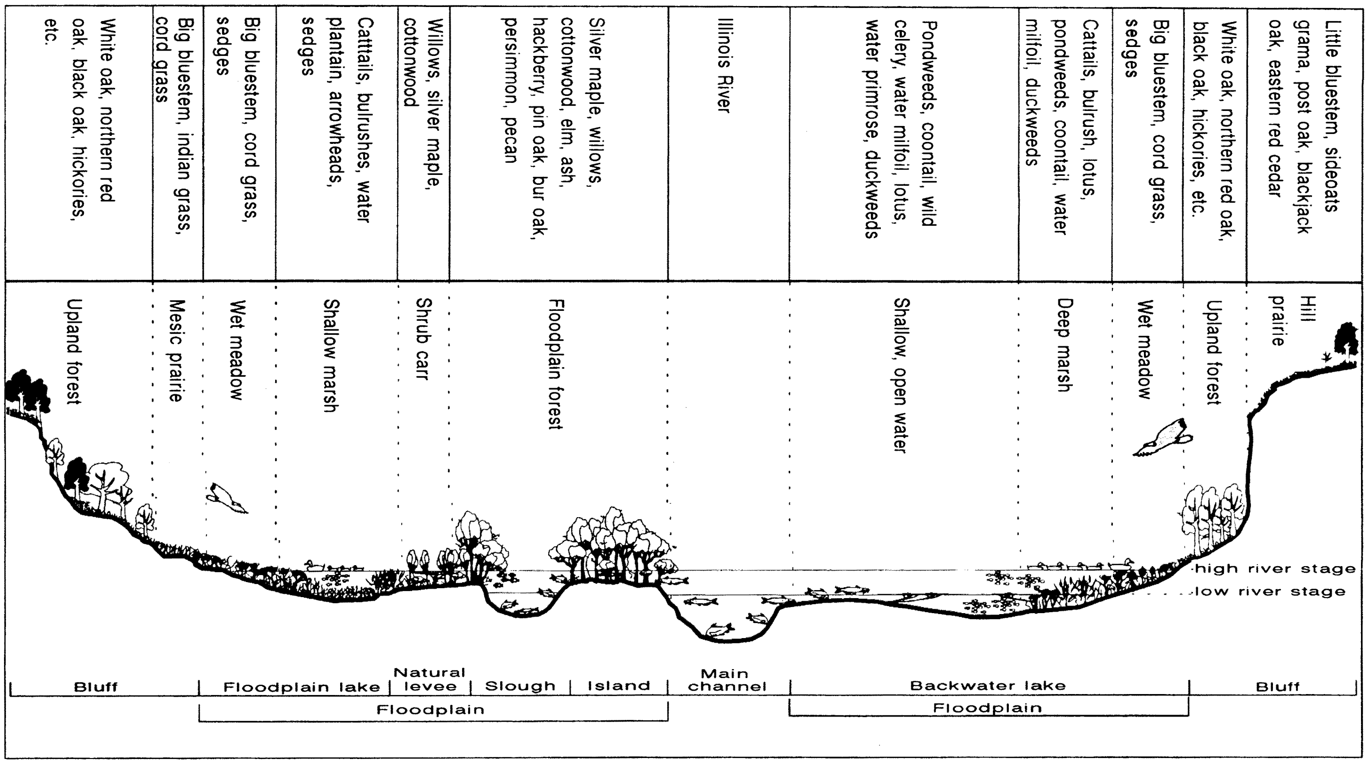

Figure 3. Representative cross-section of the natural Illinois River–floodplain ecosystem. The floodplain is seasonally inundated and includes permanent and temporary lakes and ponds. The land forms, such as the natural levees, sloughs, and islands are created by processes of erosion and deposition, primarily during floods. Each type of plant community has a certain moisture tolerance and consequently occupies a particular land form (and land elevation) depending on whether the community is adapted to permanent immersion or to seasonal flooding. Terrestrial animals such as deer and wild turkey use portions of the floodplain during low river stages. During high river stages, they move to higher ground, and fishes use the floodplain and the expanded backwaters and lakes for spawning and nursery areas. The vertical scale and channel width on this diagram are greatly exaggerated: the floodplain is 2.5–5 km wide along the middle and lower Illinois River, the bluffs are approximately 30 m high, and the main channel typically occupies only 3–6% of the total floodplain width.

ployed by natural resource agencies with the ecosystem approach. I define *ecosystem management* as working with the natural driving forces and variability in these ecosystems with the goal of maintaining or recovering biological integrity. I focus on flood pulses both because they drive these systems and because the great floods of 1993–1994 in Asia, Europe, and North America heightened public awareness, thereby creating an opportunity to change river management policies.

I draw my examples largely from the upper Mississippi River and Illinois River because I am most familiar with them. They also exemplify both the conflicts between development and conservation of large floodplain rivers that have occurred worldwide and the more recent restoration and rehabilitation efforts that are beginning in Europe and the United States.

The Mississippi River and Illinois River comprise the Upper Mississippi River System, which the US Congress designated as both a "nationally significant ecosystem" and "nationally significant waterway" (for commercial navigation) in the Water Resources Development Act of 1986 (Figure 4). The act funded a 12-year environmental management program for the river system as well as a replacement dam and greater lock capacity at St. Louis. Plans for even greater expansion of navigation capacity are currently being developed by the US Army Corps of Engineers. But federal and state natural resource agencies and several environmental groups fear that the integrity of the upper Mississippi is being compromised. They have issued their own strategies and plans for conserving and restoring the river (Robinson and Marks 1994, Upper Mississippi River Basin Association 1994, Upper Mississippi River Conservation Committee 1993).

Importance of large river–floodplain ecosystems

The public is aware of the high biodiversity of tropical rain forests, but few people realize that many of these forests are on floodplains, as in the Amazon basin. Other well-known areas that are part of river-floodplain systems include: the 80,000-square-kilometer shallow wetlands and lakes of the Gran Pantanal of the Paraguay River, the 32,000-square-kilometer Sudd papyrus marshes of the Nile, and the 18,000-square-kilometer swamps of the Okavango River in Botswana (Welcomme 1985).

Large river–floodplain ecosystems are often species rich, for a variety of reasons having to do with their age, size, habitat complexity, and variability. In the tropics, the flood pulse provides a strong seasonal cycle in an environment that is otherwise unseasonal. The flood pulse

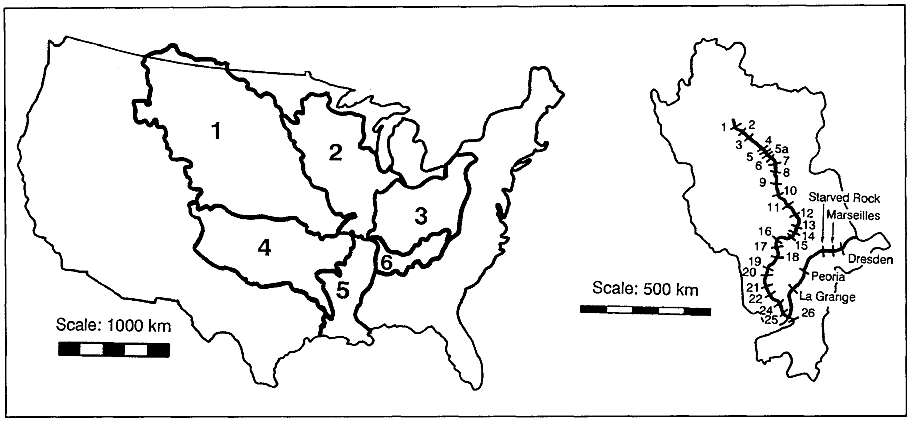

Figure 4. The six subbasins of the Mississippi River and an enlargement of the upper Mississippi subbasin (area 2). The dams on the upper Mississippi River are numbered; those on the Illinois River are named.

may have been responsible for the evolution of an annual seasonality in life cycle that eventually enabled tropical insects to colonize temperate zones (Erwin and Adis 1982, Junk et al. 1989). In rivers that are geologically old, such as the Mississippi and Amazon, species have had enough time to diversify and exploit the complex array of available habitats (Goulding 1980, Junk et al. 1989). Even hypoxic backwater swamps are occupied by many groups of fishes with a variety of physiological and anatomical adaptations to low oxygen, including air-breathing (e.g., the tropical lung fishes, *Dipnoi*, and the temperate gars, *Lepisosteidae*). Large rivers usually have numerous tributary systems where new aquatic species can form through geographic isolation (Moyle and Herbold 1987).

Species richness not only depends on speciation but also on avoidance of extinction, particularly in the temperate zones of the world with their more variable climates and periodic glaciations. The north-to-south orientation of the mainstem Mississippi across 18 degrees of latitude (approximately 2000 km) provided an escape route to southern freshwater refuges during the ice ages, when the Great Lakes and many northern rivers in both North America and Europe either disappeared under ice sheets or became too cold for warmwater species (Briggs 1986, Moyle and Herbold 1987).

The Mississippi also has not experienced the episodes of aridity that repeatedly dried up once-extensive lakes and drainages in the southwestern United States. As a result, the Mississippi and its major tributaries are home to one third of the 600 freshwater fishes in North America and most of the 297 species of freshwater mussels that occur in the United States (Fremling et al. 1989, Neves 1993, Turgeon et al. 1988). In contrast, western Europe has only 15 species of freshwater mussels (Neves 1993), and its river-floodplain systems, such as the upper Rhone in France, typically have 25 species of fish (Persat et al. 1994). The Great Lakes contain only approximately ten endemic species of fishes—the rest are mostly river residents or river migrants that have colonized the lakes on their own or been introduced by humans (Mills et al. 1994, Underhill 1986).

The Mississippi River has conserved representatives of some of the most ancient lineages of freshwater fishes including: lampreys (*Petromyzontidae*), gars, and sturgeons (*Acipenseridae*). Two families with only one or two living representatives occur in the Mississippi. The bowfin, *Amia calva*, is the only extant species of Amiidae. The paddlefish family (*Polyodontidae*) has only two living species: *Polyodon spathula* (Figure 5), in the Mississippi and its tributaries, and *Psephurus gladius* in the Yangtze River of China (Pflieger 1975).

Refuges and migration corridors. In addition to conserving species during harsh climatic periods over time scales of millennia, river-floodplain ecosystems provide refuges during annual or decadal droughts as well as corridors for spectacular annual migrations. Terrestrial animals migrate to water (e.g., in the Okavango Swamps), and aquatic animals can swim downstream to mainstem rivers from tributaries that periodically dry up (Osborne and Wiley 1992). The north-south orientation of the Mississippi and the extension of the Missouri into the arid West make these rivers ideal migration corridors for waterbirds (e.g., ducks, geese, swans, herons, and egrets), shorebirds (e.g., sandpipers), raptors (e.g., owls, hawks, and eagles), and songbirds (e.g., warblers, finches, and orioles) that move annually between their breeding grounds in the north and their wintering areas along the Gulf coast or in South America (Figure 6a). The Mississippi flyway is the migration corridor for 36% of North America's waterfowl (Havera 1992).

Most fish undertake much shorter migrations within the river-floodplain ecosystem and its tributaries, but there is one long-distance aquatic migrant that rivals the birds. The American eel, *Anguilla rostrata*, spawns deep in the Sargasso Sea, northeast of Cuba (Tesch 1977). The baby eels drift and swim with the ocean currents toward the Gulf and east coasts of the United States. The males seek out river mouths, but the females swim as far upstream as the tributaries of the upper Mississippi River in South Dakota, Minnesota, and Wisconsin, where they take 5 to 20 years to mature before starting their downstream migration (Page and Burr 1991, Pflieger 1975).

In both tropical and temperate rivers, fishes undertake both longitudinal (i.e., along the river channel) and lateral (i.e., across the floodplain) migrations to spawning and feeding areas, because optimal conditions for both activities vary with the flood cycle and do not often occur simultaneously in the same areas (Welcomme 1985). In temperate rivers, many fishes migrate to off-channel wintering areas seeking refuge from low temperatures and currents (Figure 6b). Currents require swimming to maintain position at a time when food supplies and metabolism are low. Temperatures in the main channel of the upper Mississippi River reach as low as 0°C and prolonged exposure is lethal to some fish, such as juvenile freshwater drum (*Aplodinotus grunniens*; Bodensteiner et al. 1990). In contrast to the main channel where the water is mixed top to bottom by turbulence, some quiescent backwater basins are thermally stratified, with denser, warmer water on the bottom. Only a few degrees difference is enough to enable the drum to survive. Another example in the upper Mississippi River is the largemouth bass (*Micropterus salmoides*), which swims miles to the same favored areas each winter (Pitlo 1992).

Long-distance links. Large rivers link distant ecosystems, including deltas and coastal zones, not only through animal migrations but also by the transport of water, sediments, nutrients, and contaminants. Some migrations counteract the natural tendency of materials to be carried downstream by the flowing water. Adult sockeye salmon (*Oncorhynchus nerka*) in the Pacific Northwest of the United States swim upstream from the sea to spawn and die in their natal streams and lakes. Their decaying bodies release sea-garnered nutrients in the headwaters, thereby increasing productivity and populations of invertebrates that young salmon feed upon before migrating to the sea (Krebs 1978).

No river is merely an inactive conduit in the transport process—even large rivers consisting mainly of channels can have large-scale eddies, bed-forms (sand dunes), man-made spur dikes extending out from the banks, mussel beds, and woody debris that retard the downstream flux of organic matter, sediments, and nutrients (Bhowmik and Adams 1990, Frechette et al. 1989, Soong and Bhowmik 1991). Floodplains provide even greater opportunity for retention of nutrients and production and processing of organic matter before delivery to the sea. Particles and the nutrients sorbed on them settle out in slack-water areas during floods or are ingested by filter feeders. Dissolved nutrients carried in from the main channel may be taken up by microorganisms or aquatic macrophytes growing in shallow, flooded plains. Vorosmarty et al. (1986) estimate that 35% of the total nitrogen entering the Mississippi and its tributaries from the watershed is retained or lost (through denitrification) within the rivers and impoundments before reaching the sea.

Figure 5. Paddlefish (*Polydon spathula*) taken alive from a small tributary 7.7 km (4.8 miles) upstream of the upper Mississippi River near Cape Girardeau, Missouri, 6 January 1994. Photo: Paul Cieslewicz, Long-Term Resource Monitoring Program, Cape Girardeau Field Station.

Whether floodplains are sources or sinks for organic matter and nutrients depends on characteristics of the flood and floodplain. Junk et al. (1989) define the inshore edge of a flood as it traverses the floodplain as the "moving littoral," and they hypothesize that biological productivity is stimulated by release of nutrients from the newly flooded soil. In temperate zones, production may also be boosted during spring floods by solar warming of cool channel water on the floodplain. In both tropical and temperate rivers, fish yield per acre is considerably greater in rivers with flood pulses and floodplains than in nearby impoundments where flood pulses are reduced or absent—an effect Bayley (1991) calls "the flood-pulse advantage" (see also Welcomme 1979, 1985). While this effect may be an amenity in our affluent society, it can be critically important in developing countries where protein sources for growing human populations may be expensive and in short supply (Welcomme 1985).

Organic matter produced on the floodplain or carried in by floods can be rapidly decomposed in the moist floodplain environment until the availability of oxygen becomes limiting. Flooded soils and the bottom layer of water in floodplain lakes often become anaerobic sometime during the flood cycle, so duration of the flood strongly influences nutrient fluxes. Decomposition speeds up when the water recedes, and the soils and leaf litter become oxygenated again. If the water recedes too rapidly off the floodplain, organic matter, nutrients, and newly hatched aquatic organisms may be carried into the river instead of remaining in the floodplain and permanent backwaters.

Consequences of altering natural processes, connectivity

Leveeing floodplains from their rivers to prevent flooding and enhance agricultural use of the rich alluvial soils eliminates the flood-pulse advantage to the fisheries in the remaining aquatic environment. On land, the natural nutrient-replenishment system once provided by the flood must be replaced with commercial fertilizer. Some societies practice a flood-adapted form of agriculture or harvest both fish and a compatible crop, such as rice, but intensive, high-yield agriculture often conflicts with fisheries, particularly if pesticides are used that can contaminate fish through biomagnification (Welcomme 1985).

Rivers that are channelized or leveed lack the vegetated riparian buffers and floodplains that could take up nutrients and ameliorate the effect of increased nutrient-loading of rivers and streams by run-off from heavily fertilized lands. Vorosmarty et al. (1986) used a simulation model in estimating that the nitrogen load at the mouth of the Mississippi now exceeds the presettlement load by two or three times, primarily in response to increased fertilizer-loading from nonpoint sources in the basin. These nutrients contribute to plankton blooms in the Gulf of Mexico where the plume of fresh water from the Mississippi meets sea water. The blooms of algae senesce and sink, using up oxygen in the decay process. The blooms thus contribute to the spreading zones of oxygen depletion on the bottom, which adversely affect commercially valuable fish and shrimp (Justic et al. 1993, Rabalais 1993, Rabalais and Harper 1992).

Downstream sediment transport can be interrupted by sediment trapping behind upstream storage dams, and lateral sediment transport can be interrupted by levees. Both these interruptions have serious long-term consequences. Upstream dams on the Missouri trap sediments, and the leveed delta of the Mississippi conveys sediments directly into the sea, so less sediment fans out to compensate for sediment compaction and rising sea level. Although newly deposited sediments are relatively watery and dispersed, they become more compact when they dry out and the organic matter they contain oxidizes, or when the water is slowly squeezed out under the weight of overlying sediment. The resulting subsidence and coastal erosion in the Mississippi delta threaten both man-made structures and the wetland nurseries of freshwater and estuarine species (Penland and Boyd 1985, Sparks 1992, Stanley 1988).

The same compaction processes probably occur on the leveed floodplains along the length of the Mississippi and its tributaries, augmented perhaps by the use of heavy modern farm machinery. Sedimentation is concentrated in the remaining floodplains and bottomland lakes that are still open to the rivers, so the lakes are filling more rapidly and the land elevation is rising much faster than in presettlement times (Bellrose et al. 1983, Bhowmik et al. 1986). Because land outside the levees is rising while land inside the levees is probably subsiding, the hydraulic head against the levees during floods is becoming greater. In the upper basin of the Illinois River, in addition, river flow and flood peaks have been increasing in response to a trend of wetter and cooler weather. The rainfall during the four-month flood season (March–June) has increased 25% during the last 20 years, in comparison with the previous 60 years (Singh and Ramamurthy 1990).

It is ironic that one unintended consequence of levee-building for flood protection is to increase flood heights. During great floods, floodplains become flowing extensions of the channel that help convey water downstream. Just as constriction of the main channel causes water to rise upstream of the constriction, so too does constriction of the floodplain by levees.

Table 1. Increase in flood heights for three stations on the Mississippi since intensive flood-control work began in 1927. "The tabulation shows the stage in feet of the peak discharge of 1993 as observed, and what it would have been in the pre-1927 condition. These data do not deal with the effect of any particular levee, series of levees, or reservoirs. The data merely show the cumulative effect of all the changes influencing the channel" (Leopold 1994, p. 12). Leopold obtained the data from Parrett et al. (1993) and from the US Army Corps of Engineers (1960, 1963).

Station	Year	Stage/foot	Pre-1927 feet	Increase
St. Louis, Missouri	1993	49	39	+10
	1973	43	35	+ 8
	1982	39	34	+ 5
Chester, Illinois	1993	49	33	+16
	1973	43	32	+11
	1982	41	31	+10
Keokuk, Iowa	1993	27	23	+ 4

The magnitude of the effect at a particular location depends on the physical morphology of the reach and the levees. Analyses of the 1973, 1982, and 1993 floods on the upper Mississippi River at three gaging stations with long-term records indicate that the floods are much higher than they would have been prior to the intensive flood-control work that began in 1927 (Table 1; Leopold 1994). Many factors in addition to floodplain constriction contribute to increased flood heights, and the increases in Table 1 reflect the cumulative effect of them all. The US Army Corps of Engineers is currently developing and calibrating a hydraulic simulation model that should help determine the effects of levees on flood heights. Belt (1975) and Stevens et al. (1975) analyzed the 1973 flood and suggested that both floodplain levees for agriculture and channel constriction for navigation contributed to increased flood heights. Channel-constriction works (e.g., wing dikes and side-channel closing structures) create a single deep channel that tends to be self-scouring and requires less dredging to maintain depths for navigation.

Following the 1993 Mississippi flood, an interagency review committee was charged with delineating the causes and consequences of the flood, evaluating the performance of existing floodplain and watershed management programs, and recommending programs and policies that would reduce the risks and costs of flooding and enhance the river-floodplain environment (Interagency Floodplain Management Review Committee 1994). The committee suggested: "The Administration should . . . establish the Mississippi River Basin as an additional national cross-agency Ecosystem Management Demonstration Project; and charge the Department of the Interior with conducting an ecosystems needs analysis of the Upper Mississippi River Basin." The committee stated that ecosystem management recognizes " . . . the functional relationships between living resources and physical features of the landscape" but did not define ecosystem management. The committee clearly indicated that the ecosystem-management approach is something more than the species-focused approach traditionally employed by natural resource management agencies and mandated in legislation such at the US Endangered Species Act.

Species-focused management

The species-oriented approach focuses on habitat rehabilitation and enhancement to improve areas for particular species (the term *rehabilitation* is usually applied to previously degraded areas; e.g., US Army Corps of Engineers 1991a). A common approach used in such projects is to calculate the average

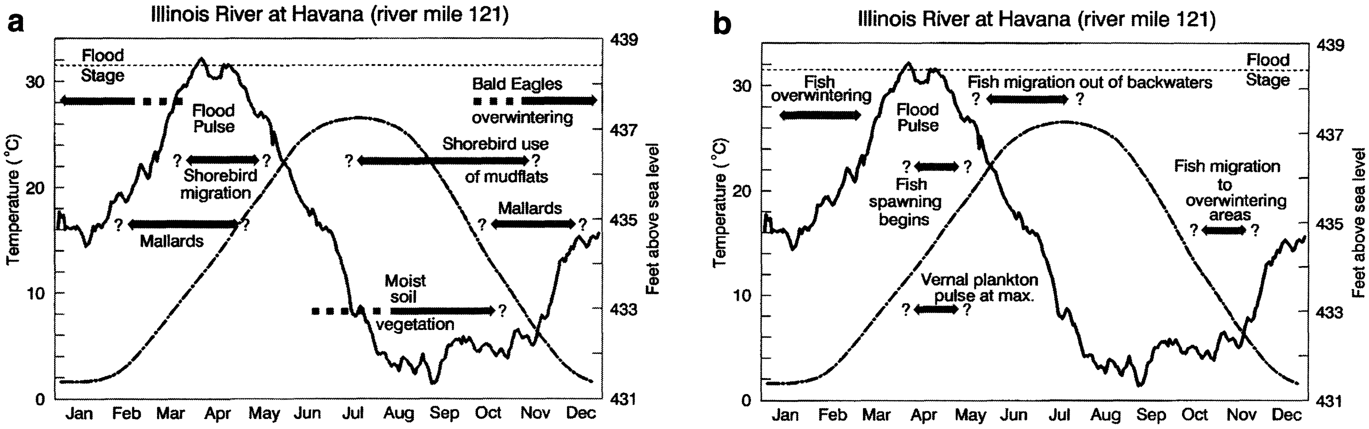

Figure 6. Use of the Illinois River–floodplain ecosystem by birds (**a**) and fish (**b**) at different stages of the annual flood and temperature cycles. For the birds, the low part of the flood pulse is just as important as the peak. Vegetation grows on the newly deposited soil that is exposed as the flood recedes. This moist soil vegetation produces seeds and tubers that ducks consume on their fall and spring migrations (**a**). Mean hydrograph (1960–1993, solid line) and water temperature (1989–1993, dashed line) at Havana, Illinois, 121 river miles upstream from the confluence with the upper Mississippi River. Flood stage (short dashed line) is defined by the US Army Corps of Engineers as the stage at which some economic damage to human structures or activities (e.g., agriculture) begins to occur on the floodplain. (**b**) Fish use the flood pulse to access spawning and feeding areas on the floodplain. Nutrients released from newly flooded soil stimulate the vernal plankton pulse, just at the time needed by larval fish. Fish migrate out of the floodplain and temporary backwaters as the water recedes in late spring. When the water begins to rise in the fall, fish seek well-oxygenated thermal refuges where the current velocity is low.

annual habitat units created over the life of the project (usually 50 years) for five or six target species (e.g., mallard ducks or muskrats), using habitat-suitability models. A habitat unit supports one individual (e.g., the feeding area that would support one duck per day during the migration period; US Army Corps of Engineers 1991b). Similar approaches are used for fish in stream environments (Bovee 1982).

The trouble with this species-oriented approach is that there are many species in large river–floodplain ecosystems, but for only a few is there enough information available to develop valid habitat-suitability models. There are 485 species of vertebrates in the upper Mississippi River (US Army Corps of Engineers 1992) and probably well more than 1000 species of invertebrates and plants. Most is known about a few game species, such as largemouth bass and mallards (*Anas platyrhyncos*), because of their value to fishers and hunters and the resulting interest in managing their populations. Less is known about some of the threatened species, such as the decurrent false aster (*Boltonia decurrens*). Moreover, there are many interactions among species, so that one species may decline because another is no longer present.

A good example is the dependency of the ebony shell mussel (*Fusconaia ebena*) and elephant ear mussel (*Elliptio crassidens*) on the skipjack herring (*Alosa chrysochloris*) for dispersal and development of their young. When Dam 19 was completed on the upper Mississippi River at Keokuk, Iowa, in 1913, it blocked the upstream migration of skipjacks. Ebony shells and elephant ears disappeared from the river upstream of the dam as the adult mussels aged and died and were not replaced with juveniles (Fuller 1980).

Optimizing habitat for a few highly valued species may create suboptimal conditions for other species or impair other services provided by rivers and their floodplains. For example, low levees and pumps are used in the upper Mississippi River to control water levels in floodplain impoundments for the benefit of waterfowl. In a few cases, high levees are maintained to exclude sediment-laden river water that would cause rapid sedimentation of the impoundment. However, levees may block currents needed by mussels or interfere with the migrations of fish to their spawning, feeding, and wintering areas.

If high levees are maintained, the floodplain cannot fulfill its hydrologic function of conveying and storing major floods, and flood heights and damages increase elsewhere. If low levees are constructed, the floodplain can convey major floods, but moist-soil plants can be protected from the minor floods that occur more frequently now than they did at the turn of the century. The impoundments are likely to receive sediment during major floods, shortening their useful life.

Even low levees may contribute to the one of the problems they are designed to solve. The more the floodplain is leveed off, the less hydraulic capacity is left to absorb the minor midsummer floods that are detrimental to moist-soil and aquatic plants. In addition, more sediment is concentrated on the remaining unleveed areas.

Because different species have different requirements and different human advocates, the approach of compartmentalizing the floodplain to optimize management for a particular group of animals (and their human advocates) can become controversial and contentious. State and federal fish and wildlife agencies may be pressured to gain more control over the water regime to satisfy constituents who see reduced wildlife populations on a favorite area in a given year as a failure of the agency or local manager.

The ongoing restoration of the channelized Kissimmee River in Florida is notable because competing interests agreed on the goal of restoring the natural hydrological regime and river configuration that had once sustained all the native species, and they specifically rejected an impounded, highly managed system (Loftin et al. 1990). The Kissimmee restoration exemplifies the ecosystem-management approach.

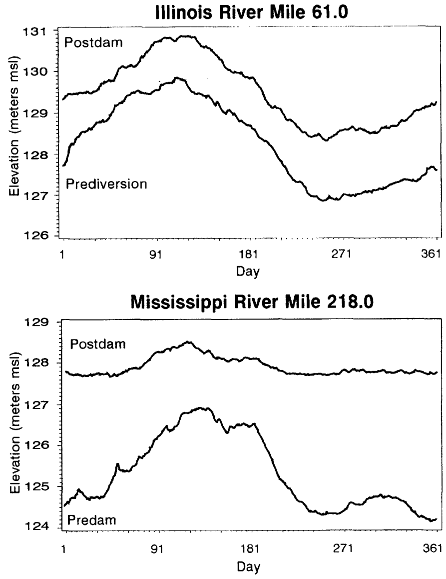

Figure 7. The Illinois River and upper Mississippi River retain flood pulses despite a century of alterations. The plotted values are daily water levels averaged over two periods of record: an early period (1878–1893) prior to diversion of water from Lake Michigan into the Illinois River and prior to dams on both rivers for the 2.74-meter (9-foot) navigation channel; and a later period (1942–1990) after the dams were completed. The flood pulses have been elevated because the navigation dams keep the rivers higher than they were naturally, but this effect does not extend all the way upstream to the next dam (see Figure 8). Lake Michigan diversion also contributed to higher water elevations in the Illinois River. Mississippi river miles refer to distances upstream from the confluence with the Ohio; Illinois river miles refer to distances upstream from the confluence with the Mississippi.

Ecosystem management

The goal of ecosystem management should be to maintain or recover the biological integrity of the ecosystem. The concept of biological integrity has been used by federal and state environmental protection agencies in the United States as the basis for biological assessment of surface waters and has been defined as "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Angermeier and Karr 1994). Angermeier and Karr (1994) state that biotic integrity includes elements (e.g., genes, species, populations, assemblages, and landscapes) and the processes that generate and maintain the elements (e.g., selection, evolution, nutrient cycling, disturbance, and succession). Indicators of biotic integrity vary with levels of biological organization, but they include range size for species, age and size structure for populations, and resilience to disturbance in assemblages and landscapes.

In large alluvial river-floodplain ecosystems, the prime abiotic factors affecting biotic integrity are water and sediment quality and the temporal patterns of water and sediment flows (hereafter called the water and sediment regimes) that shape the river channel and the floodplains themselves. These factors strongly influence habitat structure, the trophic base, and biotic interactions. Ecosystem management includes: maintaining water and sediment quality within limits that preserve biological integrity and maintaining or restoring the master processes (as defined by Power et al. article beginning page 159 this issue) that enable the river-floodplain ecosystem to maintain, repair, and rejuvenate itself. Master processes include the abiotic processes of erosion and sedimentation that maintain floodplains and deltas and the biotic processes of colonization and succession that rebuild communities following disturbances. Giving the ecosystem some scope to maintain itself is probably more cost-effective in the long run than attempting to control or replace all natural functions with human intervention. We first need to appreciate and understand the river-floodplain ecosystem and then adapt our management accordingly, like the ancient Egyptians, whose flood-adapted agriculture capitalized on the nutrient subsidy provided by the annual flood of the Nile.

Key questions in ecosystem management are how to determine the natural patterns and how to preserve or restore them within the constraints posed by human needs. I use the Danube, the Illinois, and the upper Mississippi Rivers as examples to show how ecosystem management is being practiced or could be practiced and how it contrasts with species-oriented rehabilitation and enhancement approaches.

What is the natural condition? The definition of *biotic integrity* also identifies the reference standard, that is the natural habitat of the region. From the natural habitat, one can determine how far the altered ecosystems depart from natural patterns and one can develop performance standards and management objectives for the altered systems. Reference standards for streams and small rivers can often be found because every ecoregion is likely to have some that are relatively undisturbed because they are within parks or nature preserves or simply far from human activity. Streams differ fundamentally from large river–floodplain ecosystems and cannot serve as references for the larger systems. For example, floods in streams are usually regarded as disturbances that reset conditions and communities to earlier successful stages. In contrast, the absence of a flood (e.g., during drought) is a disturbance in river-floodplain ecosystems.

Because all large rivers in the temperate zone have been altered for human use and because the watersheds of these rivers are too large to be contained wholly within a nature preserve, we do not have another, unaltered Mississippi in the United States or Danube in central Europe to compare with the altered ones. The situation is not hopeless, however. There are historical data avail-

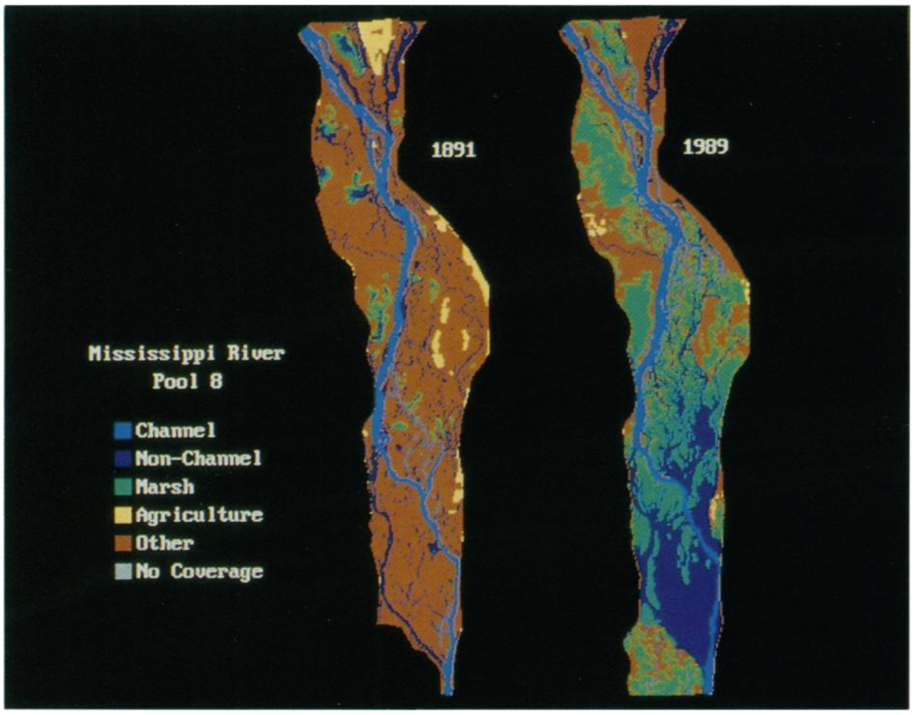

Figure 8. A century of land cover changes in a 37-kilometer reach of the upper Mississippi River floodplain, just downstream of La Crosse, Wisconsin. The border between two states runs down the center of the channel, with Minnesota on the left and Wisconsin on the right, and the distribution of land types is fairly typical of the floodplain in this northern region. The combined area of open water (light blue) and marsh (dark blue) greatly expanded, from 1556 hectares (3843 acres) to 9488 hectares (23,428 acres; from approximately 10% to 63% of the total floodplain area of 15,058 hectares [37,180 acres]) when a navigation dam completed in 1938 permanently inundated portions of the old floodplain immediately upstream of the dam. Further upstream, the river and floodplain retain much of their natural morphology, although much of what had been grasses, forbs, and trees is now marsh. In 1891, 587 hectares (1449 acres) were used for agriculture and 238 hectares (588 acres) were urban or developed. In 1989, the relative proportions had reversed: 1362 hectares (3364 acres) were developed and only 84 hectares (207 acres) were in agriculture. River reaches further south, in Iowa, Illinois, and Missouri, typically have more floodplain agriculture, up to 70% of the floodplain, much of it behind levees. Overall, approximately half of the floodplain of the upper Mississippi River down to the confluence with the Ohio has been drained and leveed, primarily for agriculture. Source: The Environmental Management Technical Center, Onalaska, Wisconsin.

able for some rivers that describe the predisturbance system (e.g., Kofoid 1903), general principles developed from studies of less-developed tropical rivers apply to temperate rivers as well (e.g., Bayley page 153 this issue), and there are relatively undisturbed reaches left within a few of the altered temperate systems (NRC 1992, Sparks et al. 1990).

The predisturbance ecosystem as a reference point. In the case of both the upper Mississippi River and the Illinois River, there are historic data, including land surveys, daily water-level records, and even scientific surveys of plants and animals extending back well more than 100 years, before the navigation dams for the 9-foot channel, diversion of Lake Michigan water into the Illinois River, and most of the draining and leveeing of the floodplains. I refer to the period from the 1870s to 1893 as the predam period and regard it as representative of the relatively undisturbed condition.

After 1892, the average rate of rise of the flood increased 22% on the Illinois River in response to more rapid delivery of water from upland watersheds, which were being modified for agriculture. Wetlands were drained, streams straightened and deepened to lower the water table, and drainage tiles installed under the fields (Kofoid 1903). The average rate of fall of the flood did not change appreciably (only 6%), because the hydraulic retention of the floodplain was not altered until levee building began in the 1920s. In 1900 the flow of the Chicago River was reversed, so water could flow by gravity from Lake Michigan, up the Chicago River, and down the newly completed Chicago Sanitary and Ship Canal into the Illinois River. As its name indicates, one purpose of the canal was to carry waste away from Chicago and thus maintain a clean drinking-water supply in Lake Michigan.

The predam Illinois River had a protracted flood pulse that benefited flood-adapted vegetation, fish, wildlife, loggers, trappers, clammers, fishers, and hunters (Figure 7). The single annual flood generally rose slowly, starting in the fall, when water loss from evapotranspiration declined because of declining temperatures and leaf senescence; peaked during spring rains and snow melt; and then declined gradually to a summer low, when plants could grow on newly deposited mudflats and in the clear, shallow lakes and backwaters (Figures 6 and 7). The pulse usually was gradual and protracted because the hydraulic capacity of the wide (2.5–5 km) floodplain was large in relation to the flow of the river. In addition, the gradient was extraordinarily shallow: the rate of fall in the lower 360 km was only 2 cm/km (Hajic 1990, Mills et al. 1966, Talkington 1991). Also, the dense vegetation on the natural levees and surrounding the lakes slowed the water (and filtered out some of the sediment). Consequently, in most years the filling and emptying of the floodplain took a relatively long time.

In contrast, the upper Mississippi River had two distinct flood pulses per year. The lowest river stage occurred in midwinter, which probably reduced overwinter survival of fish, because some were trapped in shallow areas that froze solid (Figure 7). The Mississippi water level probably dropped in winter, because the drainage extends further north where tributaries are more likely to freeze and snow is less likely to melt in midwinter. The gradient in the Mississippi was steeper, so the flood rose and fell more quickly than in the Illinois. Rapid declines in water level increase the proportion of young fish stranded on the floodplain. Also, the major flood did not begin as soon in the spring as on the Illinois, where fishes had earlier access to floodplain spawning and feeding areas. These differences in the natural flood pulses between the two rivers may explain the greater fish yield in the Illinois River at around the turn of the century (Mills et al. 1966). Having established the predisturbance reference point, the next task is to determine the current condition of the ecosystem.

Assessing the changes. Despite a century of alteration, flood pulses still occur on approximately half of the original floodplain area of the Illinois and upper Mississippi Rivers where there are no levees (Figure 7). People are surprised by this occurrence, because they know the rivers have been dammed, and they assume the flow is controlled. The purpose of navigation dams is to maintain minimal water depths for boat traffic during the low-flow season (i.e., the river stage is not allowed to drop as low as it did naturally). These dams do not stop floods.

In fact, most of the 28 dams on the upper Mississippi River are designed to pass flood flows with little blockage, by having gates that lift completely out of water and earthen weirs (fixed-crest spillways) that are overtopped. Any blockage of flow would raise water levels upstream against levees, increasing seepage rates and pumping costs and increasing the risks of levee overtopping or failure. Even where there are no upstream levees, blockage of the river would increase flooding above what would naturally occur in the unconstricted river. Therefore, the federal government would be liable for damages or would have to buy more flood easements or land.

The same design features that pass flood water also allow sediment to move through the dams, so the main channel does not silt in upstream of the dam. The gates are raised from

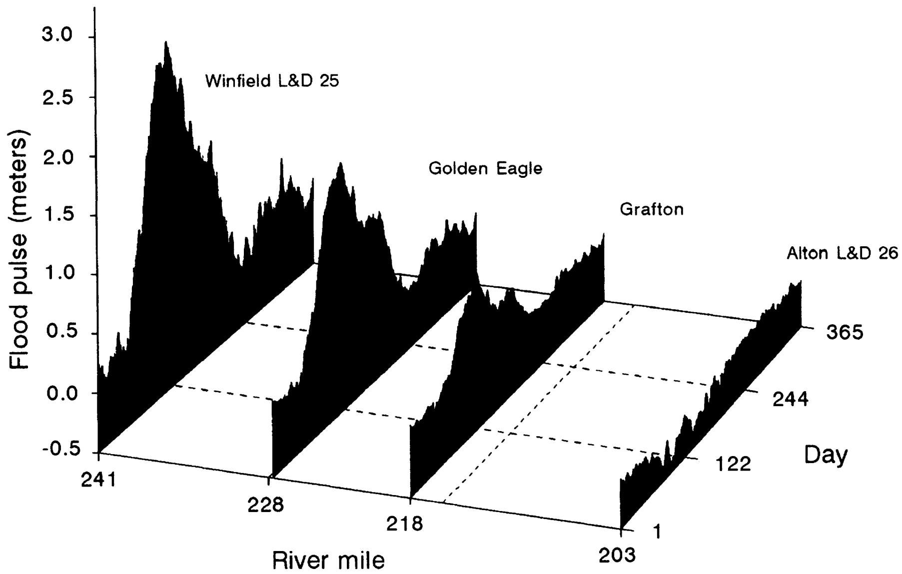

Figure 9. A natural flood pulse occurs at Mississippi river mile 241, 64.4 km (40 miles) upstream of the navigation lock and dam (L&D 26) at river mile 201. The closer to the dam, the more the flood pulse is attenuated by operation of the dam. Near the dam, at river mile 203, the flood pulse is actually inverted—the river drops during the spring flood and rises during the summer low flow. The period of record is 1942–1990. Each of the four gage readings is adjusted so that zero is the mean low water level occurring in the summer low-flow season. The gages are identified by their river mile location and the name of the nearest town (Winfield, Missouri, and Golden Eagle, Grafton, and Alton, Illinois). L&D 25 at river mile 241.5 demarcates the upstream boundary of this river reach.

the bottom of the river, so water and sediment flow under the gates. Siltation does occur in areas lateral to the main channel where the current velocity is low.

Two dams on the Illinois River (La Grange and Peoria; Figure 4) have a different design that fulfills the same purposes. These dams consist of a series of adjacent panels that are hinged to a sill at the bottom of the river. The panels swing up and are propped in place during low flows to hold back water. During high flows, the props holding the panels are removed and the panels fold down onto the bottom. Boats can go right over the top of the folded panels without having to waste time going through the locks.

Although the flood pulse still occurs in the upstream portions of the navigation reaches, it is attenuated downstream and even inverted near some of the dams. This attenuation occurs because, in an effort to maintain a constant depth further upstream, the river is kept artificially high near the dam and then lowered when river flow begins to increase (Figures 8–10). Opening gates and lowering the surface elevation of the river increases the slope of the river between the upstream gaging station and the dam, thereby increasing the rate of flow without raising the water-surface elevation at the upstream gage. This complicated operating procedure minimizes inundation of the lateral floodplains and avoids costs of land acquisition or flood easements. Less upstream land is flooded with the operating procedure that uses an upstream gage than with the simpler procedure of just trying to maintain the water elevation at the dam (Figure 9). Either procedure is capable of maintaining adequate water depths for boat traffic.

The inversions, where water is low during the flood season and high during the summer, are especially harmful because the timing is wrong for the biota. The floodplain is exposed when fish need access to shallow spawning areas, then inundated when moist-soil plants should be growing on mud flats. If the plants do germinate, they are drowned by rising water during what should be their normal growing season. The water drops in the fall, just when migrating waterfowl, which prefer to feed in shallow water rather than on land, need access to the summer's production of tubers and seeds.

Altered flood pulses can initiate long-term changes in the ecosystem that are difficult to reverse. Because navigation dams do not allow the rivers to get as low as they once did, sediments delivered by the annual floods into areas influenced by the dams do not dry and compact during the summer, as they formerly did (Bayley 1991). During the 1950s, the impoundments created just behind the dams efficiently trapped sediments that were being delivered to the river at increasing rates as agriculture intensified (with a shift to row crops, fall plowing, removal of streamside forests, and stream straightening; Bellrose et al. 1983). As the bottom was raised, the sediments were more easily and frequently resuspended by wind- and boat-generated waves, making the water cloudy. The last of the floodplain trees that had been killed by permanent inundation rotted or were carried away. With these natural wave-breaks gone, banks eroded at increasing rates, putting even more sediment into the lakes and removing even more windbreaks as whole islands eroded away. The waves were bigger on the greatly expanded lakes and backwaters because the wind fetch was greater, so aquatic plants were uprooted. They could no longer function as biotic mediators, reducing sediment resuspension and turbidity by damping waves with their leaves and anchoring the bottom with their roots (Sparks et al. 1990).

Restoring the floodplain, backwaters, and lakes. The landforms of the natural river-floodplain ecosystem were an equilibrium product of predam water and sediment regimes. The plant and animal communities, in turn, had adapted to use these regimes and landforms and even resisted disturbances (e.g., plants maintained clear water by resisting wind-generated waves that resuspend sediments and erode shorelines). While significant portions of these ecosystems remain intact, other portions have been altered by increases in the sediment load and changes in the water regime (e.g., more rapid and more frequent fluctuations and permanent inundation of the floodplain) that eventually led to loss of the biotic mediators, aquatic vegetation.

From a geological perspective, the river is simply building itself new floodplains by filling the permanently inundated areas with sediment. The new sedimentary equilibrium that is likely to be reached in some places as early as 2050 might look like the predisturbance floodplain but at a higher elevation (Bhowmik et al. 1986). A less desirable scenario is that the new floodplain in the vicinity of the dams will lack topographic relief (e.g., natural levees and swales) and therefore have less habitat diversity, because the range of variation in water level has been reduced by the dams. Sedimentation and deposition can only build land to the height of the flood (i.e., sediment does not jump out of water). Because the range between the average flood height and the average low flow is now reduced in comparison to the predam era (because the dams keep the water higher during the low flow period; Figure 7), the range of land elevation is likely to be less as well.

The combined predictive expertise of fluvial geomorphologists and ecologists is needed to address these questions. In the meantime, it is important to reduce sediment loading of the main river by treating watersheds, tributary channels, and riparian zones to reduce soil erosion. Such treatment is likely to also help reduce the extreme fluctuations in water delivery that characterize the altered tributaries, thereby smoothing the flood pulse in the main river. The same practices also would reduce the pesticides and excessive nutrients that are delivered to the main rivers in dissolved form or attached to soil particles (Goolsby et al. 1993).

Some proposed suggestions for arresting or reversing the sedimentation that is occurring are clearly impractical. Dredging the 14 million metric tons of sediment the Illinois River deposits annually in its floodplain and backwaters, much less what the upper Mississippi River deposits, would bankrupt the nation (Lee 1989). Raising the navigation dams to deepen and expand the lakes and backwaters is likely merely to increase the sediment-trapping efficiency and the wind fetch, so these larger muddy lakes are likely to last only 20–30 years until they fill with sediment to approximately their current water depths.

The most that probably can and should be done is to guide the sedimentation that is occurring now, perhaps by installing deflection dikes to keep some areas scoured out, while increasing the rate of sedimentation elsewhere. The intent would be that when the river finally attains sedimentary equilibrium, it would look something like it did in 1900. In contrast to existing navigation structures that close off side channels and spur dikes that confine the river flow to the 9-foot navigation channel and keep it scoured out, these new structures would divert some flow to create or maintain side channels. If some areas must be dredged, the embryonic natural levees and islands that form behind the deflection dikes would be logical places to put the dredge spoil. Gore and Shields (page 142 this issue) discuss the design, application, and ecological and hydrological effects of various sediment control structures, and spur dikes in particular.

In the predisturbance river-floodplain ecosystem, low, broad natural levees once screened floodplain lakes and backwaters from winds and the silt loads of the river. In some places, flood water not only had to cross the natural levees but also shallow wetlands before it could reach lakes that were farther away from the river. These lakes thus were doubly protected from sediment by a natural system that we could imitate.

Restoring the annual flood pulse. The flood pulse could be restored to more of the river if the mid-reach control procedure for operating the dams, which causes inversions of the flood pulse, were replaced with dam control (Figure 10). Moving the control points to the dams would require federal purchase of additional flood easements to accommodate more extensive flooding. The Interagency Floodplain Manage-

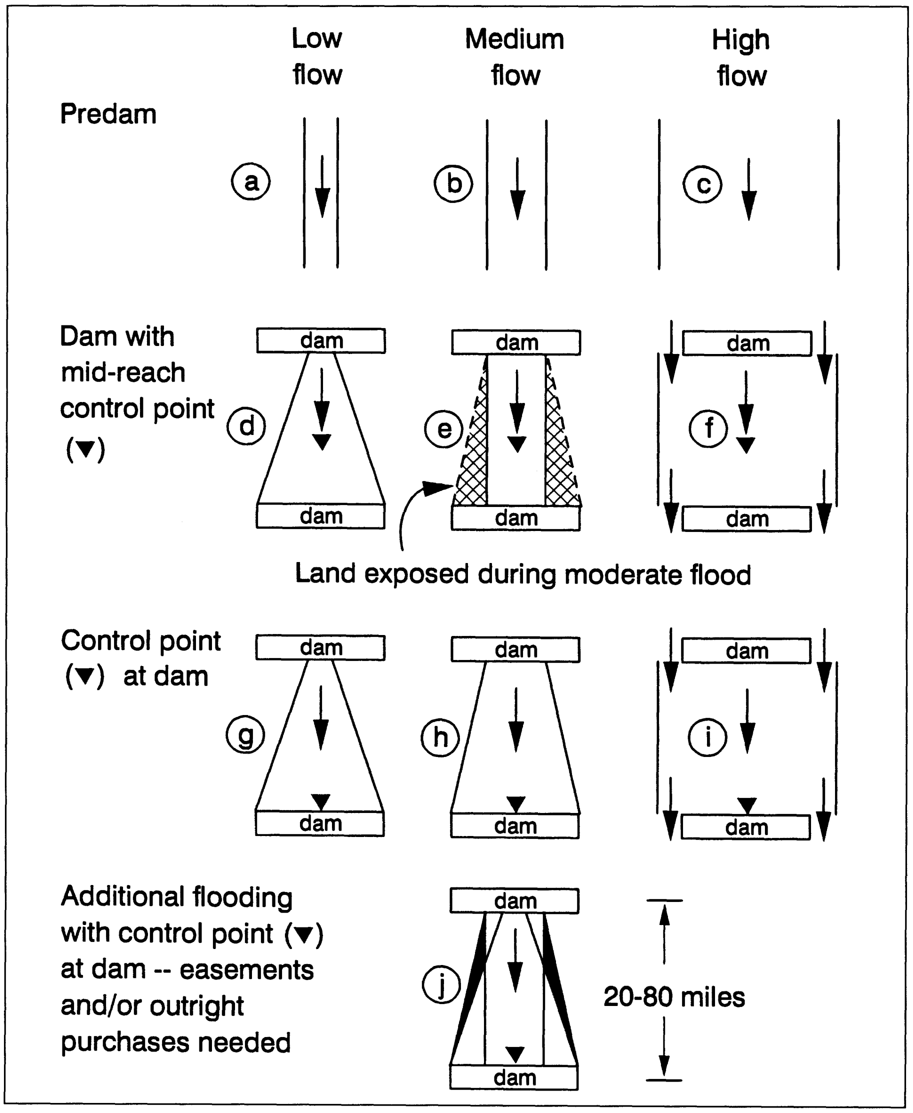

Figure 10. Effect of two alternative dam-operating procedures on flooding patterns upstream of navigation dams. In the predam era, the extent of lateral flooding was directly related to flow in the river: the greater the flow, the higher the water elevation, and the farther the water spread onto the floodplain (compare **a**, **b**, and **c**). Arrows indicate direction of flow and solid triangles indicate the position of river elevation gages on the river reach. The operating objective for navigation dams is to maintain a constant water level at the gage, so that minimum depths are maintained for commercial boat traffic. The navigation dams on the upper Mississippi and Illinois Rivers do not stop major floods and the overflow pattern consequently is the same with or without dams (compare **c**, **f**, and **i**). During low and intermediate flows, however, the dams do change the natural pattern. During low flows, the gates on the dam are partially closed, raising water levels near the dam and permanently inundating portions of the floodplain. The inundation pattern is the same regardless of whether the control gage is located at the dam or at mid-reach (compare **d** and **g**). At medium flows, however, the inundation pattern does vary with the location of the gage (**e** and **h**). In order to maintain a constant water elevation at mid-reach during moderate floods, the downstream gates must be opened far enough that the water level is drawn down near the dam, thereby increasing the water slope and accelerating the flow (**e**). A side effect is that the former downstream floodplain is exposed when river flow increases (compare **d** and **e**)—just the opposite of the natural pattern seen in **a** and **b**. The alternative procedure, with the control gage at the dam, does not invert the flood pulse, benefiting native vegetation, fish, and wildlife that are adapted to a natural flood pulse. Operating with the control gage at the dam causes slightly more flooding than with mid-reach control, so additional land or flood easements must be purchased by the federal government (the dark areas in **j**). Purchases of floodprone land or easements are consistent with national policies of restoring wetlands and rivers and reducing flood risk and damage (Interagency Floodplain Management Review Committee 1994).

ment Review Committee (1994) noted that buying out floodprone land and structures reduces future flood damages as well as restoring the floodplain, and it has recommended that the US Army Corps of Engineers consider shifting to dam point control. This approach could also ameliorate an expensive conflict in operating procedures of two federal agencies. In the summer, the corps holds water levels up for navigation, while the US Fish and Wildlife Service and state conservation agencies try to drain their moist soil impoundments. During the typical fall flood, the corps lowers water levels near some of the dams, just when the impoundments need to be flooded.

Restoring long-term variability. Some year-to-year variation in the flood pattern is probably necessary to maintain a full complement of species (e.g., some plants may require an unusually long summer low-flow period to set seed and replenish soil seedbanks). Other plants, such as cottonwoods, may require a rare combination of extreme events: a major flood that provides fresh mud flats with no shading from competitors, followed by several years of low flow that enable the seedlings to grow large enough that they are not swept away or drowned by the next flood. Extreme events may even have a rejuvenating function; for example, record floods may rejuvenate some long-abandoned side channels by scouring away accumulated sediment.

Creating an ideal water regime for certain species every year is probably unnecessary and even undesirable, as long as a mosaic of habitats exists. Then, spawning, feeding, and overwintering can occur somewhere in the river-floodplain ecosystem within accessible range of local populations, even if the same area is not used for the same purpose every year. A floodplain depression that is ordinarily dry during moderate floods may become a spawning site during record floods, when traditional sites are unusable because of excessive water velocities or sediment loads. Although the water regime might be suboptimal in a given year for fish, most warmwater fishes are adapted to a variable system by means of a high reproductive potential that enables them to quickly make up for lost year classes (Bayley 1991, Junk et al. 1989).

Migrant waterbirds behave opportunistically. If they fail to find food or suitable resting places, they are able to move over levees and over land to other drainages and to man-made, inland cooling lakes and reservoirs. For example, when the food supply for diving ducks failed in the Illinois River in the late 1950s, they shifted to the upper Mississippi River (Mills et al. 1966).

Applicability to other rivers. Countries with heavily developed floodplains and high population densities find it difficult to restore floodplains. It is therefore remarkable that the Netherlands, one of Europe's most densely populated countries, is preparing to rehabilitate and recreate some side channels and portions of the floodplain of the Rhine River (van Dijk and Marteijn 1993).

An even more ambitious plan is being promoted by the Dutch World Wide Fund for Nature (WWF 1993). There are two dike systems along the Rhine in the Netherlands: high dikes set back from the river, called winter dikes because that is when the river levels are highest, and low dikes set near the river, the so-called summer dikes that keep small floods off agricultural areas (the forelands) between the two dike systems during the growing season. Flood heights have been rising because of aggradation of the floodplain on the riverside of the winter dikes. The dikes are subject to erosion from wind-generated waves when the river is in flood. WWF proposes to increase the flood conveyance capacity of the forelands by stripping off accumulated clay deposits (the clay is a valuable raw material for bricks) and exposing former side channels, some of which would circumvent the navigation dams and provide fish passage. Summer dikes that are not functional or that increase flow resistance and flood heights would be razed. Portions of the floodplain would be allowed to revert to forest to protect the winter dikes from waves and ice.

The Danube is another European river that flows through heavily populated areas, yet levees are set back and portions of the original floodplain retain their forests and side channels (WWF 1993). Developing countries could capitalize on these experiences by planning now to retain floodplains and flood pulses, rather than attempting to restore them later at considerably greater expense.

Windows of opportunity. Some river alterations foreclose opportunities to maintain or restore functioning river-floodplain ecosystems at low cost, without engineering structures. On both the Danube and the Missouri Rivers, upstream storage reservoirs trapped sediment so the water coming out of the dams had increased capability to pick up sediment from the bed thereby causing the channels to deepen. Channel deepening occurs at least 346 km downstream of the last major reservoir on the Missouri (Hesse et al. 1989). Downstream floodplains are dewatered as the average river elevation drops lower, so that floodplain wetlands and wildlife habitat are lost (Hesse et al. 1989, Pearce 1994). On the Missouri, bed degradation finally ends where the Platt River tributary resupplies the Missouri with sediment. On the Danube, however, the upstream loss of sediment requires a series of downstream dams to maintain water levels (Pearce 1994). Such dams would also generate electric power. Water would be metered into the wetlands via control gates along a ship canal that takes 90% of the Danube water and bypasses the old floodplain. Because less than 10% of the original flow of the Danube remains in the original channel, weirs would have to be built across the old river bed to raise the level of the river so fish can swim into the wetlands. Low levees and culverts control water depths and flow across the wetlands. Nevertheless, even in this highly controlled system, the water levels could be manipulated to simulate the original flooding regime.

The upper Mississippi and Illinois Rivers are unusual in that the navigation dams do not stop floods and there are no large storage reservoirs disrupting the annual flow of sediment and water. Thus, these rivers avoid the downstream problems that plague the Missouri and the Danube. Moreover, approximately half the original floodplain remains unleveed and open to the rivers. This area may be one of the few places in the developed world where ecosystem management can be fully applied to large river–floodplain ecosystems.

Ecosystem management works with natural processes such as erosion, sedimentation, and seasonal flood pulses, attempting to guide them rather than completely thwart them. Hunters, fishers, and preservationists who are now at loggerheads over how much land, money, and management effort is to be devoted to this or that species could find common ground in restoring the floodplain and the flood pulse that maintains all the species.

With world attention focused on the disastrous floods of 1993–1994, now is a good time to consider ecosystem management of these large river–floodplain ecosystems. Nonstructural approaches to flood management, such as not rebuilding damaged structures in floodprone areas and moving people out of harm's way, are congruent with restoration of floodplains and riparian zones (Interagency Floodplain Management Review Committee 1994, NRC 1992). Ecosystem management could actually save money and increase economic efficiency in the long run, because natural services are restored (e.g., flood storage, conveyance, and moderation; water purification; production of fish and wildlife; and preservation of biodiversity) instead of being maintained by human intervention at great cost and considerable risk of failure. Allowing phenomenally productive river-floodplain ecosystems to preserve species and produce fish and wildlife is probably cheaper and less problematic than building and operating hatcheries and zoological parks.

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