Can Large Rivers Be Restored?

Most restoration projects are only attempts to rehabilitate selected river sections to a predetermined structure and function

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Riverine ecosystems are remarkably resilient in their ability to recover from physical and chemical disturbances. If disturbance occurs as a pulse (a rapid instantaneous alteration; as defined by Bender et al. 1984), recovery to the ecosystem's original condition often occurs. However, if the disturbance is sustained (a press disturbance) and causes a complete loss of critical habitat elements, ecological integrity cannot be maintained. Because running water ecosystems are so intimately tied to physical, chemical, and biological processes that occur throughout the catchment, *restoration*, by its strictest definition as a return to original condition, is a complex and difficult task. Most so-called restoration projects are, more properly, attempts to rehabilitate selected sections of riverine systems to a predetermined structure and function. Most often, rehabilitation involves the provision of a new chemical and physical structure, which enhances formation of the biotic community.

Restoration and rehabilitation projects on small streams and rivers have been common practice for many years, and a considerable body of knowledge on restoration techniques and expectations of success exist (Gore 1985, Newbury and Gaboury 1993). However, restoration and rehabilitation projects for large river systems are far less common (Regier et al. 1989), and there is little ability to predict success or monitor recovery (Gore and Milner 1990). Furthermore, restoration projects for large rivers, particularly those with high channel erosion potential, are extremely expensive (Kern 1992). Accordingly, the National Research Council (1992) has identified the development of adequate restoration techniques for all aquatic ecosystems as a priority area for research in applied ecology.

Renewal of physical and biological interactions between the main channel, backwaters, and floodplains is central to rehabilitation

Ecosystems of large, undeveloped rivers are based on interactions between the main channel and adjacent low-velocity habitats during weeks of overbank flooding (Welcomme 1989). Spatial and temporal habitat heterogeneity are created by erosion and deposition as the channel migrates back and forth across the floodplain. It follows that restoration of large rivers to a pristine or virgin state is incompatible with present human population levels (Welcomme 1989). Instead, the logical goal is the rehabilitation of developed river systems, that is, the recovery of some of their ecological functions and values.

Even though the major rivers of the world display considerable individuality in gradient, magnitude and frequency of meander, channel geometry, and chemical and biological composition, human impact on these systems has followed a remarkably uniform pattern (Welcomme 1989). During the last 250 years large-scale engineering works have transformed major temperate-zone rivers (Table 1). At current rates of dam construction, 60% of the world's total streamflow is likely to be regulated by the year 2000 (Petts 1989a).

Presently, a number of ecologically rich, broadly meandering, and braided (multichannel) rivers with large floodplains (e.g., the Missouri, Willamette, Rhine, and Vistula Rivers; see Table 1) have been confined to single channels with slight sinuosity, high flow velocities, and extremely low levels of habitat diversity. Channel bed degradation that follows this channelization isolates the river and its tributaries from floodplain water bodies, often by draining abandoned channels and oxbows (a large, U-shaped bend in a river; Brookes 1988, Lelek 1989). Human development of floodplain

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Table 1. Large-scale engineering works have transformed the world's major large temperate-zone rivers during the last 250 years. (Adapted from Shields et al. in press.)

River	Distance from river mouth (km)	Impact on habitat	Impact on fishery
Mississippi (United States)	0–1570	River length shortened 229 km. Floodplain reduced 90% by levees.	Unknown.
Missouri (United States)	0–1181	River length shortened 64.4 km. Water area reduced 34–66%. 2111 km^2 natural habitat lost from channel and meander belt.	Commercial fish harvest reduced 80% in reach within state of Missouri.
Sacramento (United States)	0–311	Freshwater wetland vegetation acreage in valley reduced 43% between 1939 and mid-1980s.	Mean fall-run chinook salmon numbers upstream of RK 391 reduced 87% between 1950–1959 and 1980–1985.
Willamette (United States)	0–301	Fourfold decrease in surface water volume. Elimination of braided reaches. Removal of 550 snags per linear km.	Unknown.
Rhine (Western Europe)	0–1320	Backwaters, braids, and side channels greatly reduced. Bed degradation up to 7 m. Area subjected to flooding reduced 85–94%.	Continuous decline of catches since 1915.
Vistula (Eastern Europe)	0–640	Elimination of islands and braided reaches, particularly in the lower course of the river. Channel width reduced by 50%. Bed lowered 1.3 m (reach from Wloclawek Dam to Swiecie).	Sharp decline in commercial fish harvest, especially of migratory species.

lands requires flood control, and levees have often been constructed so that flooding is nearly eliminated (Dister et al. 1990). These activities tend to reduce or eliminate backwater habitats such as side-arm channels, oxbow lakes, sloughs, and inundated floodplains and replace them with more uniform terrestrial habitats and main channel or reservoir pools (Figure 1). Existing habitats are often filled by natural sedimentation, and comprehensive stabilization of the river shape and form prevents channel migration processes that form new backwaters (Petts 1989b). For example, along the lower Missouri River, construction of dikes and revetments (embankment facings, such as boulder rip-rap) coupled with closure of upstream dams has resulted in conversion of almost half of the aquatic habitat to terrestrial habitat (Hallberg et al. 1979, Morris et al. 1968). Similar changes have been reported for the Vistula (Babinski 1992).

Large river rehabilitation requires some combination of placement of vegetation; development of structures, such as dikes and artificial riffles (i.e., shallow, rocky areas of moderate to high velocity), to re-

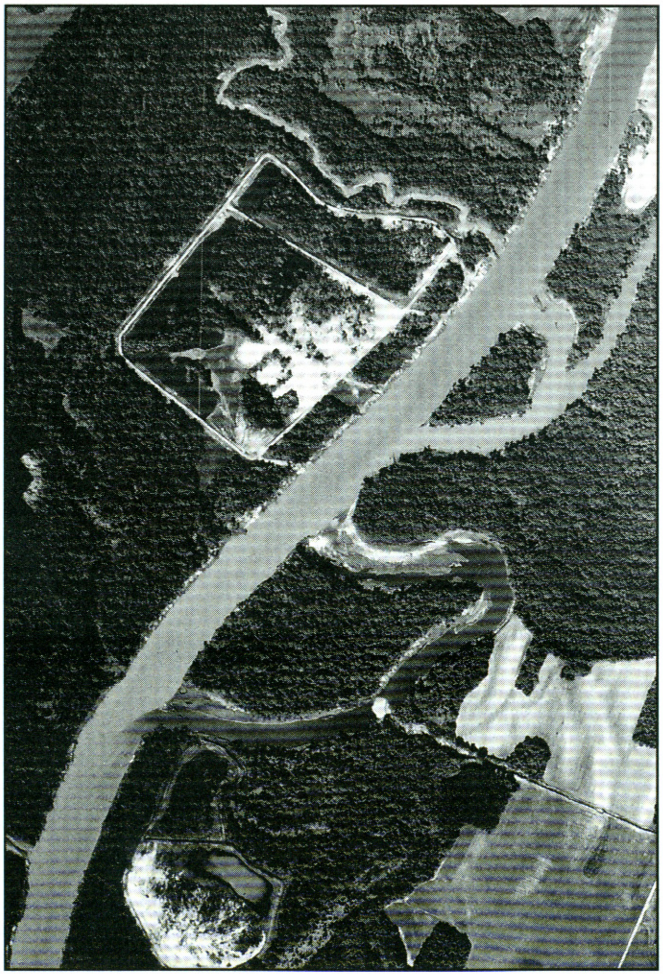

Figure 1. Impact of construction of the Tennessee-Tombigbee Waterway on riverine habitats. The waterway is the wide, gently curving channel in the middle. Note sediment deposition in severed meanders of the Tombigbee River on the right. Courtesy of US Army Corps of Engineers, Mobile District.

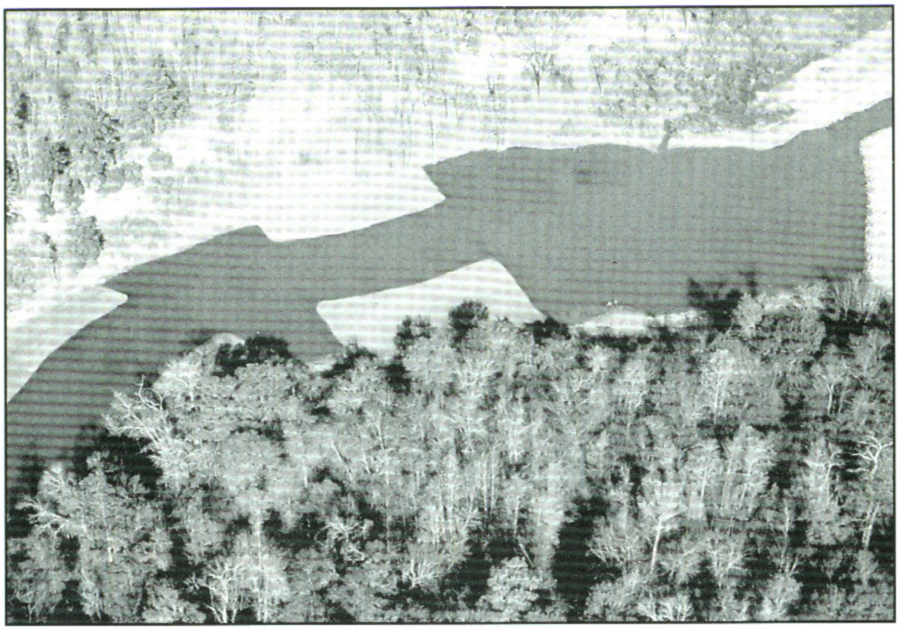

Figure 2. Artificial riffles (Tombigbee River, Mississippi) located in old river channel with a constant discharge from an adjacent reservoir. Courtesy of US Army Corps of Engineers, Mobile District.

store lost geomorphic diversity; action to ameliorate floodplain isolation (Regier et al. 1989); and remediation of water-quality degradation (Sparks et al. 1990). Populations of selected fish species are sometimes restored by stocking operations. In this article, we focus on habitat, although the literature contains some impressive success stories of large river water-quality restoration (e.g., Douglas and McCreanor 1990 and Romano et al. 1992) and interesting discussions of fish stocking and aquaculture.

Rehabilitation of disturbed river systems rarely includes artificial population of new habitat zones but instead focuses on improving the existing habitat quality and quantity. In turn, the improved areas become attractive to potential colonists, which eventually establish permanent resident populations. The rate of recovery to a predisturbance community or a stable target community (which may not resemble a predisturbance community but is an acceptable alternative) is determined by the extent of the disturbance (Cairns 1990), its spatial scale (Poff and Ward 1990), the availability of natural sources of nutrients (DeAngelis et al. 1990), and the location and stability of sources of colonists (Gore and Milner 1990). Critical to many decisions in the regulation of potentially disturbing human activity is the ability to predict the resilience of the running water ecosystem. In most instances, predictive ability is limited by knowledge gaps in a host of topics including spatial scales required for ecosystem functioning; links between streams, riparian zones, and groundwater; and reliable environmental indicators.

Rehabilitation of large rivers presents complex technical problems. Although positive responses have been reported for local, small-scale treatments (e.g., construction of a single artificial riffle), more ambitious rehabilitation must consider the riverbed, the floodplain, and tributaries, as well as the role of a stabilized or restored catchment.

A clear vision of the rehabilitated system must be developed by first identifying the ideal outcome from an ecosystem standpoint, which can then be modified based on economic and political restrictions (Kern 1992). Design details should be guided by the identified outcome and a diligent and imaginative evaluation of available techniques. Alternatives in large river rehabilitation have been cataloged by Petts et al. (1989), Regier et al. (1989), Schnick et al. (1982), and Welcomme (1989). These alternatives may be grouped as manipulations of the channel, backwater area treatments, riparian zone and floodplain alterations, and flow regulation. Rehabilitation activities within river channels address three critical habitat needs for biota: substrate quality and distribution, availability of cover, and hydraulic conditions. Often, the placement of a single structure enhances more than one of these habitat criteria.

River channel manipulations

Substrate quality and distribution. The inorganic particles, stony material, and organic debris that make up the channel bottom substrate offer footholds for plants and invertebrates, sites for deposition and incubation of eggs, grit for grinding food, and refuge from a variety of physical and chemical extremes such as flood, drought, and temperature change (Minshall 1984, Statzner et al. 1988). The streambed surface acts as a trap for organic material and the interstitial (spaces between particles within the bed), or hyporheic, area can be one of the primary, so-called faunal reservoirs for recolonizing reaches following disturbance (Williams 1983).

The distribution of sediment sizes along a river is one of the primary physical habitat factors influencing composition of lotic communities. The overall distribution of substrate particles is related to frequency and magnitude of flood events and human activity, which dislodges material from the bed. Within a reach, larger particles are associated with faster currents and smaller particles with slower flows. Bed stability usually decreases as average substrate particle size decreases. Although all sediment sizes have some habitat value for select species (burrowing invertebrates prefer sandy bottoms, while many filter-feeding insects require a stable, hard substrate surface), highest productivity and diversity of benthic organisms occurs in riffle habitats of medium cobble (approximately 150 mm diameter) and gravel (Hynes 1970), and this relationship has been generally found to be true in rehabilitated streams (Gore 1985). Fine sediments or areas of continually shifting sands reduce macroinvertebrate species abundance and richness (Minshall

1984), which, in turn, may affect fish species composition (Milhous 1982). In sand-bed rivers, much of the macroinvertebrate production used by higher trophic levels occurs on woody debris (Benke et al. 1985).

In small streams and rivers, substrate rehabilitation techniques focus on the maintenance of clean, high-velocity riffle areas. Placement of stone structures (e.g., weirs—low-elevation dams with notches to release surface flows; spur dikes—structures to divert flow away from the bank; and revetments) deflect and accelerate flows across a defined area to flush fine sediments away and expose larger particles (Reiser et al. 1989). Large-scale addition of gravel and cobble (artificial riffle) is used to control river bed erosion (Kern 1992). Placement of largely untrimmed timbers to stabilize channel morphology and maintain pool and riffle frequencies is frequently advocated and increasingly popular in areas where large woody debris is a dominating physical feature of natural stream and river systems (Bilby and Ward 1991, Magsig 1990).

Because they are impediments to navigation, many of these structures are impractical in large river systems. Most frequently used are structures, such as spur dikes, that accelerate flows across shoals of gravel and cobble. The placement of woody debris is restricted to application as isolated revetments. The construction and placement of artificial riffles of gravel and cobble is sometimes considered.

Construction of artificial riffle areas, offering diverse substrate types, promotes establishment of benthic communities. For example, two artificial riffles were constructed in a remnant of the Tombigbee River immediately below a dam on the Tennessee-Tombigbee Waterway in Mississippi (Figure 2; Miller et al. 1983). The riffles were an experimental replacement of numerous, ecologically rich riffle habitats eliminated by waterway construction. Each riffle was 46 m long and 24 m wide and was capped with 2–80 mm diameter coarse sand and gravel. Before restoration, reach communities were impoverished, having less than ten macroinvertebrate taxa and

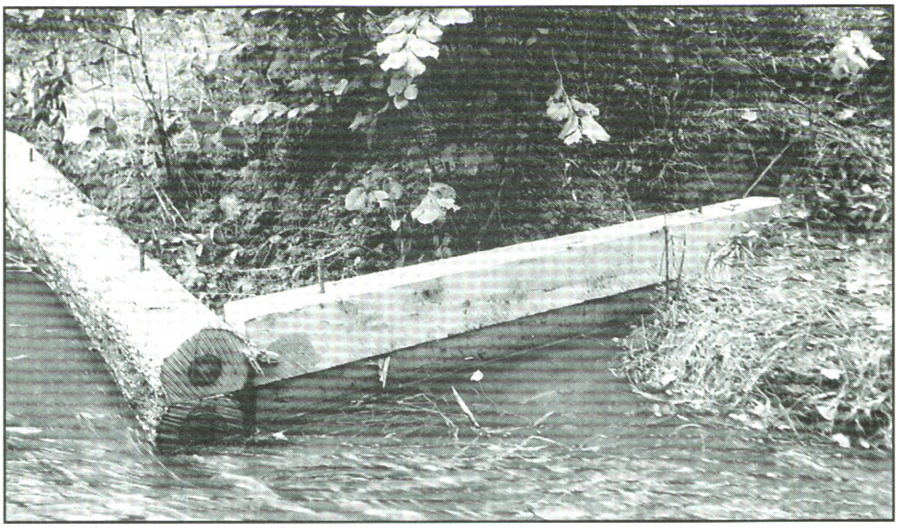

Figure 3. Restoration structures commonly used in small rivers. Deflectors (**top**) and log weirs (**bottom**) have their structural equivalents and comparable effects in large river applications.

less than 15 resident fish species. Approximately 20 macroinvertebrate taxa colonized the riffles within four months of construction, and 42 species of fish were collected during the first two years after construction.

In another project, an artificial riffle was constructed in Kentucky in the Ohio River by depositing a 30 m × 150 m area with gravel larger than 9.5 mm to a depth of 25 cm (Miller et al. 1983). Unfortunately, the riffle was later eroded or covered by sand during high flows. The short-term value of the riffle was not evaluated.

We do not know of any successful creation of a riffle in a large river subject to flow variation (areas downstream of hydropower or flood storage dams). The most likely areas to require substrate rehabilitation are riffles in the tailwater; they are the most impoverished because of the influences of deep, cold-water releases and unpredictable changes in flow pattern. These same rapid changes in flow pattern make the placement of artificial riffles nearly impossible, because they are readily degraded in the immediate tailwater or covered by redeposited sediments farther downstream (i.e., aggradation; Gore 1994).

Cover availability. Cover refers to instream and overhead features, which provide fish protection from high current velocities and predation. For example, overhanging vegetation, undercut banks, submerged vegetation, submerged objects (e.g., logs, roots, boulders, and cobble), floating debris, and turbulence in the water column all provide such refuge (Giger 1973). Cover needs vary diurnally and seasonally, as well as by life stage and species (Wesche 1985). The reduction or loss of cover in river ecosystems may reduce fish populations by up to 80% (Wesche 1985). Submerged cover (e.g., undercut banks, depressions in the bed, or large boulders) has been shown to be important to almost all fish species for effective completion of life cycles. Indeed, many species (especially Cyprinids and some Percids) use this refuge for all phases of the life cycle from egg laying and incubation to adult foraging. Other species of fish (such as Salmonids) establish territories around a cover object.

Instream cover structures used for small stream rehabilitation include spur dikes (or deflectors), weirs, boulders, logs, and other woody debris (Figure 3). These structures foster formation of low-flow pool areas, which provide protection from high velocities and cover from predators. Placement of instream cover structures in large navigable rivers is restricted by the cost and size of structures durable enough to withstand flow forces and floods yet not impede navigation. However, structures used to control bank erosion and deepen navigation channels do provide structural cover in large rivers. Unfortunately, long-term effects of these structures have frequently been detrimental. Sediment deposition in low-velocity areas between and adjacent to spur dikes has greatly reduced water surface area and backwater habitat along the Missouri River. Effects of such structures along the lower Mississippi River have been less severe, either because the structures are lower relative to high river stage or because sediment deposition is much slower when compared with the Missouri (Nunnally and Beverly 1986). Several techniques for enhancing spur dike habitats, such as excavating gaps in the structures, have been proposed and tested with success (Shields 1984, Shields et al. in press) and are likely to be the recommended practice for controlling associated sedimentation problems.

Hydraulic conditions. Aquatic organisms are restricted as to the flowing environments they can occupy. The hydrodynamic forces acting against organisms compel them to expend energy to forage and reproduce. As a result, compromises between body morphology to compensate for pressure and friction drag and the ability to acquire sufficient energy for growth and reproduction appear to limit benthic organisms to a narrow range of complex hydraulic conditions (Statzner et al. 1988). Indeed, some organisms that change body shape and configuration over the life cycle (e.g., the water penny, *Psephenus* spp. and other genera of the family Psephenidae in the Coleoptera) are restricted to very different flow regimes during different stages of growth and/or reproductive behavior. Similar restrictions appear to apply to many fish species. Scarnecchia (1988) found that fish species with poorly streamlined bodies, such as sunfish (*Lepomis* spp.) and carp (*Cyprinus carpio*), were quite abundant in areas containing pools or backwater areas but were eliminated from swift, uniform channelized reaches, lowering overall species abundance and diversity.

Rehabilitation should produce river reaches with near natural levels of spatial and temporal heterogeneity of hydraulic conditions (Bravard et al. 1986). Structures should be placed or removed to create a variety of depths and velocities over a variety of substrates. Restoration of physical habitat diversity attracts and fosters a biological community of high diversity and density (Gore 1985). Among techniques used to foster naturally diverse hydraulic conditions are the retention or addition of artificial riffles and woody debris (Shields and Smith 1992), construction of spur dikes and weirs, and restoration of meanders.

Low-head weirs have been employed in large rivers to provide sediment control and dampening of high-discharge events from hydroelectric facilities and to enhance the frequency of pool and riffle combinations (usually five to seven channel widths between riffles; Leopold et al. 1964). These structures are typically less than two meters high and are designed to alter hydraulic conditions rather than to store water. Weirs provide a pool and sediment trap upstream and a plunge pool and accompanying riffle downstream.

In small streams, weirs are frequently used and are made from logs, native rock material, and gabions (cobble and boulder encased in wire mesh). However, in larger rivers, weirs are almost always engineered structures of concrete (Figure 2). Where blockage of migratory fish is of concern, fish passageways can be incorporated into these structures. Brookes (1988) has described design criteria for weirs, and Schnick et al. (1982) have described the construction of many fish passage devices to be incorporated into such structures. Weirs are obviously impractical for large navigable rivers but have been shown to dramatically enhance trout habitat by reducing discharge surges associated with generation of hydroelectricity on tributary rivers of the Cumberland River (Curtis et al. 1987).

Because of their impact on floodplain hydrology, weirs should be used with great care. A series of ten low-level (3-meter) weirs and upstream storage reservoirs has had detrimental effects on the ecosystem of the Murray River in Australia (Walker and Thoms 1993). Temporary wetlands have been permanently flooded, and the nature of the littoral zone has been transformed, contributing to declines in the range and abundance of many native plants and animals. In general, the location of weirs on large rivers should be restricted to areas where creation of pools is not likely to jeopardize critical riparian habitat and where regulating downstream flows is not likely to alter the availability of floodplain habitats. In most large rivers such locations are rare.

Although widely practiced in small streams (Brookes 1987), meander restoration has limited application on large rivers because of cost and complexity of the engineering activities required. Nonetheless, at least two meander restoration projects for major rivers are currently underway. Florida's Kissimmee River was channelized between 1962 and 1971 for flood control (Figure 4; Toth et al. 1993). In the process, 166 km of river was transformed from a meandering channel into a straight 90-kilometer-long canal. Restoration of the natural system, involving backfilling the canal, diverting flow through the old channel, and modifying upstream flow regulation practices to reestablish historical hydrologic patterns is currently planned.

This restoration design is to be based on results of a demonstration project conducted between 1984 and 1989 that included construction of three weirs in the canal, which diverted flow through adjacent sev-

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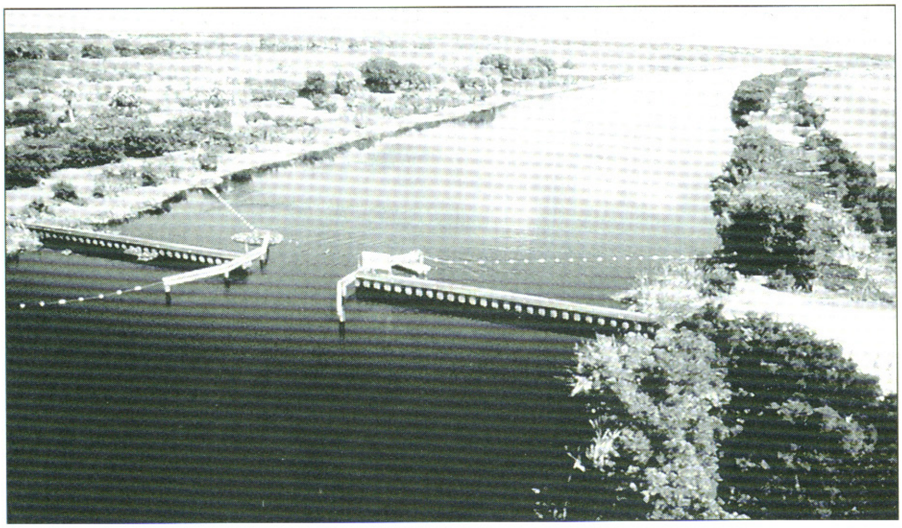

Figure 4. The Kissimmee River, Florida, showing (**a**) a straight canal constructed in 1960s with remnants of the sinuous channel scheduled for restoration and (**b**) a restoration demonstration with a metal weir constructed to divert water flow through the severed meander. Photos courtesy of South Florida Water Management District.

Figure 5. Embankment constructed at upstream entrance of severed meander to divert sediment laden flows, Verdigris River, Oklahoma. Courtesy of US Army Corps of Engineers, Tulsa District.

ered meanders and nearby floodplain. Habitat and biological responses to the demonstration were positive. The restoration of floodplain characteristics led to rapid reinvasion of hydrophitic plants (*Polygonum, Panicum,* and others) and a concurrent reduction in xeric plants. Rheophilic (current-seeking) species of aquatic insects dominated the restored sections and phantom midge populations were reduced. Increased use by wading birds and a tenfold increase in fish densities were also observed.

A meander restoration project is also under consideration for the Danube in Germany (Kern 1992). Detailed plans for restoring two meanders include the provision of gently sloping, rock drop structures that are to divert base flows into the old channel yet allow high flows to use the present (straightened) channel. Natural floodplain habitats are to be restored, and the purchase of a 100-meter strip of land (the predicted maximum meander belt width) along concave banks is to allow unrestricted bank erosion in order to restore natural channel cross-section and bed morphology.

Backwater treatments

The role of vegetation in the river corridor and the value of floodplain ponds as refugia and nutrient sources are important considerations in restoring ecosystem integrity. Methods for rehabilitating river corridor habitats are diverse (Schnick et al. 1982) and have included planting aquatic macrophtyes (Sparks et al. 1990), as well as techniques to create or maintain severed meanders (Shields and Abt 1989) and natural oxbow lakes (Figure 5; Sowl 1990). Combinations of dredging sediments from backwaters and placement of the materials dredged to build islands or levees are common (Berry and Anderson 1986). Backwater habitat values are dependent upon at least seasonal if not continuous hydraulic connection to the main river channel. Restoring this connection is often proposed for isolated backwaters (Bravard et al. 1986). Borrow pits, excavated to obtain soils for levee or dam construction, often fill with water and can be managed and protected to provide backwater habitats (Nunnally et al. 1987).

An ongoing program of environmental management along the upper Mississippi (Patin and Hempfling 1991) and Illinois Rivers (Donels 1989) is possibly the most ambitious effort ever undertaken to protect and restore backwaters. Backwaters are to be restored by dredging and diversion of main channel flow and protected by construction of levees and training works. The prognosis for long-term success is uncertain, particularly in light of the sedimentation that occurred during the 1993 flood.

Riparian zone and floodplain alterations

Riparian zones along developed rivers are often degraded by erosion, encroachment by floodplain development, or bank stabilization structures. If designed properly, bank stabilization offers erosion control and some instream cover. Bank protection devices made of stone with a wide range of sizes offer a diversity of refugia, providing superior habitats to steel or concrete structures. Intermittent structures like spur dikes are better for fish habitat than continuous protection like stone blankets (rip-rap; Figure 6; Shields et al. in press).

Recently developed concepts in large river engineering involve the use of vertical vanes placed on the channel bed to reduce nearshore flows and control bank erosion, eliminating the need for disturbing the riparian zone. However, these devices are somewhat experimental and cannot be universally applied (Niemi and Strauser 1991, Odgaard and Spoljaric 1986).

Structures composed of living plant materials or woody debris are typically preferred from an environmental standpoint (NRC 1992), but some sort of inert structure is usually required to protect banks along larger rivers where hydraulic forces are great and periods of inundation long. Designs featuring stone for lower bank protection and various types of vegetation for upper bank protection are growing in popularity (Henderson 1986). Initial costs for streambank protection (approximately \$30 to \$60 per linear meter of streambank) involving planted vegetation vary widely. Some investigators have reported costs for woody vegetation ranging from one-fourth that of stone blanket (Roseboom and White 1990) to an order of magnitude greater than that for stone (Hemphill and Bramley 1990). In the long term, costs for planted vegetation may be less than for engineered structures, which must be maintained and replaced (Coppin and Richards 1990).

Along many major rivers, bank stabilization has become so extensive that removal or drastic modification of bank protection structure to "restore the capacity for geomorphological renewal" (Bravard et al. 1986) has been suggested as a habitat rehabilitation measure. Compensation of landowners for resultant erosion is usually required. This goal may not be realistic for the rehabilitation of many of the world's major large river systems because sustained construction on the floodplains has gone on for centuries. The costs to relocate whole communities in order for rehabilitation to proceed would be prohibitive and certainly unpopular.

Ecological values of floodplain habitats along leveed rivers can sometimes be restored by constructing new levees more distant from the channel (so-called setback levees). This approach has been followed along the Danube in The Czech Republic (Welcomme 1989). The existing mainline levee system along the lower Mississippi River is set back several hundred to several thousand meters. Setback levees permit controlled inundation of adjacent floodplains and allow the river to meander within a belt-width prescribed by levee dimensions. Bayley (1991) suggested that an interim first step in "restoring the watershed" of large, highly regulated rivers might be the accommodation of natural flooding over the contiguous river-floodplain area by purchasing land, removing levees, and modifying reservoir operations along selected river reaches between dams along the river. In some cases, floodplain hydrology can be restored by simply turning off pumps that are used to remove interior drainage during floods (Sparks et al. 1990) and excavating breaches in levees at selected locations (Kern 1992).

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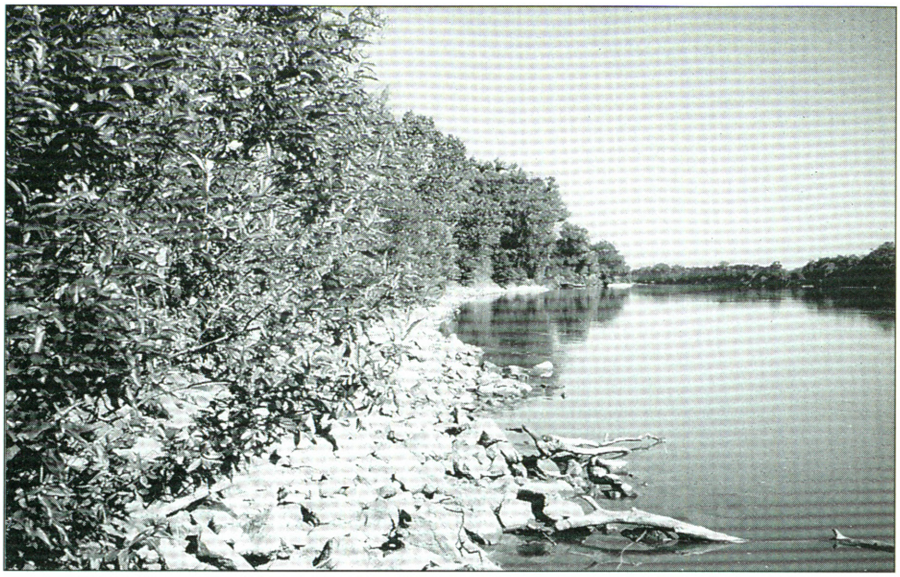

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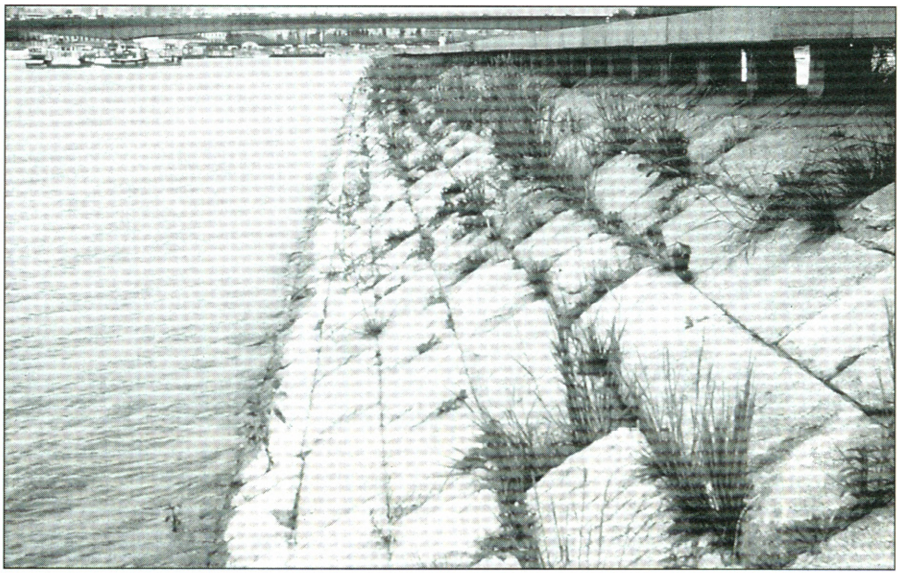

Figure 6. Streambank protection structures made of a wide range of stone sizes create more diverse habitat (**a**) than do those made of uniform concrete blocks (**b**). These structures can protect riparian vegetation from erosion. However, successional processes in the riparian are normally driven by flooding, erosion, and deposition. Photos from the Sacramento River in California.

Flow regulation

Flow regulation by dams and diversions is a key component of virtually all large river development programs. Alteration of flood timing, magnitude, frequency, and duration disturb both terrestrial (Walker and Thoms 1993) and aquatic communities (Toth et al. 1993). Accordingly, modification of regulation practices to achieve habitat goals is usually necessary for ecosystem rehabilitation.

Flow regulation may be coupled with other measures, such as with meander restoration (as proposed for the Kissimmee River; Toth et al. 1993). This regulation strategy often involves significant costs in terms of reduced flood control, hydropower, or other water resource benefits (Walker and Thoms 1993). Numerical models (Nestler et al. 1989) have been developed to predict habitat availability under various regulation strategies.

Predicting recovery rates

Assuming that water quality problems have been mitigated and that habitat quality has been enhanced in a disturbed area, the rate of recovery is dependent upon the avail-

Table 2. Levels of disturbance in streams and rivers, location of instream source of colonizers, and observed time scales of recovery. Disturbance levels are defined by channel condition and the source of instream colonists. (Modified from Gore and Milner 1990.)

Disturbance level	Channel condition	Source of colonists	Recovery pattern	Time scale
1A	Entirely destroyed	None	Primary succession	5–25 years
1B	Entirely destroyed	Hyporheic	Primary/secondary succession	1–5 years
2A	Reach destroyed	Upstream and downstream	Primary succession	90–400 days
2B	Reach destroyed	Upstream, downstream, and hyporheic	Secondary succession	40–250 days
3	Species abundance reduced in reach	Upstream, downstream, and hyporheic	Secondary succession	25–100 days
4	Species abundance reduced in patches	Upstream, downstream, and hyporheic	Secondary succession	10–75 days

ability and location of a source of colonizing organisms. Although research results vary, reinvasion of macroinvertebrate and fish species is relatively rapid (Milner 1994). Thus, the central focus of large river restoration is habitat rehabilitation.

Gore (1985) noted that initial colonization of restored river channels follows the patterns described by island biogeographic theory but that long-term predictions break down because the distance between so-called islands (newly created habitat) and the source of colonizers (upstream, downstream, and hyporheic reservoirs) decreases as colonization progresses. Although there have been few long-term studies of recolonization of reclaimed and rehabilitated river channels, those that have been conducted indicate a deterministic pattern of colonists. Upon development of a biofilm, periphyton, especially diatoms, colonize new substrate rapidly (in some cases in less than ten days) followed by invertebrate grazers and collectors able to use periphyton and accumulating organic particulates. Finally, predatory invertebrates arrive in the community. Where the riparian zone has been significantly disturbed, the arrival of leaf-processing shredders, normally early colonists, may be late—coinciding with the regrowth of riparian trees.

Fish species tend to follow the same patterns as invertebrates. Forage fish arrive after sufficient numbers of invertebrates invade to form a food source, and finally top carnivores arrive after forage fish populations are established. Because many adult fish are territorial, invasion is likely to be by nonreproductive larvae and juveniles. Establishment of a stable fish community structure may take several years (often the length of the life-cycle of the species of interest) to match predisturbance conditions.

Gore and Milner (1990) proposed four levels of disturbance and predictions about rates of recovery as guidelines for stream and river managers. The rates of recovery are based upon the spatial scale of the disturbance (from isolated patches to entire streams), the type of community development (mimicking primary succession, where undeveloped, often inorganic substrates/soils exist, or secondary succession, where a persisting organic substrate enhances community development), and the availability, size, and proximity of instream colonization sources (e.g., upstream, downstream, and hyporheic; Table 2).

Time scales to attain a stabilized community are quite broad in each category, which is less a result of the lack of long-term studies and more a result of the variability in the source distance factors and the types of colonizers available to colonize a given area. In most cases, shorter recovery times are a result of colonization dominated by drift of aquatic insects from upstream areas and highly mobile fish species.

Colonization includes the contribution from aerial adult colonizers of the benthic insect families. When drift contributions to the newly forming community are not available, the rates of recovery decrease dramatically. However, there are exceptions. For example, the construction of an artificial gravel bar in a large river is equivalent to a level 2A disturbance, and it might be reasonable to predict that attainment of a stable community would take less than one year. Because large river benthic communities can be dominated by low-frequency drifting species or nondrifting species (e.g., mussels), establishment of many insect species is dependent upon deposition of eggs from flying adults. Without aerial colonizers contributing eggs to the developing community and the reliance on slow oversubstrate migration and small amounts of drift, Bingham and Miller (1989) found that recovery rates increased to three years.

Conclusions

Despite the individuality of large rivers, most that have been impacted by humans have undergone comprehensive stabilization of channel shape, form, and discharge pattern, as well as gradual elimination of natural off-channel habitats. The stability and sustained function of large river ecosystems is dependent upon maintenance of watershed and floodplain integrity. Each contributes to the physical and biological interactions that define the structure of large river ecosystems (Sparks et al. 1990). Restoration, then, provides the physical and biological structure upon which natural processes of recovery can build and progress toward an acceptable level of ecosystem function. As such, it should not be expected that artificial structures (hard or soft) are likely to have any degree of permanence.

The process of restoration or rehabilitation is an attempt to direct biological and geohydrological process toward an end point at or near predisturbance conditions. When considering the magnitude and complexity of factors that contribute to the organization of large river ecosystems, defining an acceptable end point is difficult. For large rivers, Milner (1994) suggests that abiotic end points (e.g., physical habitat quality and water quality) may be the most appropriate targets rather than biological end points (e.g., density, diversity, or production of certain species or trophic levels), which have been most commonly evaluated in smaller river and stream ecosystems.[1] Indeed, when considering the range of disturbances that have occurred in the watersheds that contribute to the structure of large river ecosystems and the alterations of large rivers themselves to suit the needs of navigation and land development, the task of truly restoring large river ecosystems would be a daunting, if not impossible, one. Cairns (1990) considers restoration activity to have been less than successful unless there also exists a self-sustaining community that is able to respond to natural disturbance through processes of succession and adaptation. If these systems require constant management, true restoration has not been achieved.

Although restoration of large rivers to a pristine condition is probably not practical, there is considerable potential for rehabiliation, that is, the partial restoration of riverine habitats and ecosystems. Renewal of physical and biological interactions between the main channel, backwaters, and floodplains is central to the rehabilitation of large rivers. Experience with large river rehabilitation is rare relative to smaller streams, probably due to the cost and the complexity of the physical and biological systems involved. Although symposia have enumerated specific research needs to determine the ability of stream ecosystems to recover from disturbance (Gore et al. 1990), these same needs must be also met in order to improve the ability to rehabilitate large river systems. That is, it is still necessary to elucidate the ecological processes that are critical to maintaining large river ecosystem integrity, the scale and quality of large river habitats, life history–disturbance interactions, and recolonization processes. This research process often requires long-term testing and monitoring of proposed rehabilitation techniques.

Proposals and concepts for large river restoration are much more abundant than are demonstrations. However, it has been demonstrated that localized rehabilitation projects have been successful. The challenge that awaits those who value rivers is to readdress this imbalance while protecting large rivers from further degradation.

[1]A. M. Milner, 1994, personal communication. University of Alaska, Anchorage.

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