RESEARCH

Restoration Ecology of Riverine Wetlands: I. A Scientific Base

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ABSTRACT / Ecological restoration is a recent discipline that should be conducted scientifically and rigorously to move from a trial-and-error process to a predictive science to increase its success and the self-sustainability of restored ecosystems. The recent research developments in ecosystem dynamics allow scientists to provide a strong theoretical base for restoration ecology. Most large rivers have been degraded and managed by various agencies, but riverine wetlands are now recognized as providing numerous valuable functions. Numerous opportunities are available to ecologically restore wetlands disappearing through terrestrialization. After a brief description and discussion of several restoration projects carried out in riverine wetlands, we propose precise recommendations for future restoration projects, which should include the following essential steps: (1) increase restoration legitimacy with a team of interdisciplinary scientists working on the project—it can thus be conducted on a strong theoretical base derived from recent ecological concepts; (2) define precise and correct restoration mission, goals, and objectives, and appropriate performance indicators of restoration success or failure; and (3) monitor ecosystem changes both before and after the restoration, and compare these changes with changes observed in reference ecosystems.

Importance of Wetlands

The most widely valued function of wetlands, particularly for riverine wetlands, is their contribution to the maintenance of regional biodiversity. They increase fish productivity in fluvial hydrosystems (Holcik and others 1981, Welcomme 1985, Amoros and Roux 1988) and are also used by fauna coming from the main channel as refuges during floods and accidental pollution, and returning as a source of colonizers (Müller and Meng 1990). In addition wetlands carry out hydrologic functions (for example, flood-peak reduction, shoreline stabilization, groundwater recharge) and water quality improvements (sediment accretion, nutrient uptake), all of which are recognized as valuable to society as a whole (Adamus and Stockwell 1983, Larson 1990, Ward 1992). For individuals, wetlands also provide recreational, educational, research, economic, and aesthetic functions.

Riverine as well as other types of wetlands are often severely altered or have completely disappeared (Finlayson and Moser 1991). For example, in industrialized countries where large rivers have been embanked for at least the last century (Lammens and Marteijn 1992), lateral erosion has been stopped. Nowadays, fluvial dynamics can not create new ecosystems (Bravard and others 1986), while such wetlands exhibit successional processes that lead to eutrophication and then to terrestrialization (change from a wetland to a terrestrial ecosystem due to bottom aggradation by the accumulation of organic matter and/or sediment deposition and/or the lowering of the water level; for example, Amoros and others 1987a). Consequently, the lack of regeneration by fluvial dynamics will lead to the disappearance of lentic ecosystems and other wetland areas that contribute to the functions of river floodplains. These include sustaining the ecological integrity of river systems (Cairns 1994) and ecological regulation within fluvial hydrosystems (Amoros and Petts 1993). Efforts to restore riverine wetlands are complicated by the hydrologic and sediment regimes that have been changed in most rivers, which make it impossible to return wetlands to their natural condition without massive removal of dams and repairing of channelization. Nevertheless, since wetlands are increasingly recognized as being of great value for water-quality protection, fish and wildlife habitat, flood control, and bank stabilization, numerous restoration opportunities are available to ecologists (Denny 1992, Lammens and Marteijn 1992, National

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Research Council 1992). However, ecological functions must be balanced against other human interests (safety against flooding, agriculture, navigation) (Feierabend 1990, Havinga 1992).

What Is Restoration?

The concept of ecological restoration, accomplished using ecological engineering (Odum 1962, Odum and others 1963) or ecotechnology (Uhlmann 1983, Straskraba and Gnauck 1985, Mitsch and Jørgensen 1989), has evolved rapidly. It differs from environmental engineering, which concerns the management of wastes and solving pollution problems (Vesilind 1993), and usually involves energy- and resource-intensive operations (Mitsch 1993, Odum 1994). The recent American Society for Ecological Restoration (SER) defined restoration as "the intentional alteration of a site to establish a defined indigenous, historic ecosystem. The goal of this process is to emulate the structure, functioning, diversity, and dynamics of the specified ecosystem." Aronson and others (1993) suggested using the term "restoration *sensu stricto*" to describe endeavors corresponding to the SER definition, as opposed to restoration *sensu lato*, which seeks simply to halt degradation and to redirect a disturbed ecosystem in a trajectory resembling that presumed to have prevailed prior to the onset of disturbance. In the same way, Lewis (1990) defined restoration as a return "from a disturbed or totally altered condition to a previously existing natural, or altered condition by some action of man," but "for restoration to occur it is not necessary that a system be returned to pristine condition." Finally, the National Research Council (1992) defines restoration of aquatic ecosystems as "the reestablishment of predisturbance aquatic functions and related physical, chemical, and biological characteristics" (see also Cairns 1988a, Lewis 1990). However, achieving 100% similarity of a restored system to predisturbance conditions is virtually impossible because restoration usually means "returning an ecosystem to a close approximation of its condition prior to disturbance" (National Research Council 1992). Furthermore, restoration is a holistic process not achieved through the isolated manipulation of individual elements (Cairns 1988b, Eiseltová 1994), and the objective is to emulate a natural, self-regulating system that is integrated ecologically with the landscape in which it occurs and requires minimal maintenance. Another important aspect of restoration ecology that should be emphasized is its difference with other concepts such as ecosystem management and creation (Figure 1). Management (Grumbine 1994) simply involves permanently controlling the state of the ecosystem to direct its changes (for example, to control the water level in a wetland to attenuate water volume fluctuations). In contrast with restoration (return to a former natural condition), creation, reclamation, or reallocation involves the conversion of an ecosystem (for example, a nonwetland habitat type) into a different ecosystem (for example, a wetland) where it never existed (Lewis 1990, National Research Council 1992, Aronson and others 1993). After its creation the new ecosystem state may be self-sustaining even if it is artificial (man-induced) or may require permanent maintenance with addition of energy, water, or fertilizers (Aronson and others 1993).

We think that restoration ecology should be built upon a strong theoretical base (rather than empiricism) and should be defined as returning an ecosystem to its condition prior to disturbance (if known and possible), or, as in most cases, to a state as similar as possible to that which prevailed prior to disturbance (Figure 1), according to the changes that have occurred in the watershed (water quality alteration, changes of sediment yield, regulation of river hydrology, and so on). This should be done by supplying the smallest amount of energy by acting on the degraded ecosystem structure and/or function through the manipulation of various ecosystem elements (state variables) and/or preferably, using reversible processes (Amoros and others 1987a) and taking into account recent ecological concepts to increase self-sustainability of restoration. We also recommend the use of soft engineering in contrast to the hard, hydraulic engineering approach. Thus, the ecosystem state after restoration should be self-sustaining (requiring minimal maintenance or management or no maintenance at all), and the natural dynamic ecosystem processes should operate effectively again.

Wetland Restoration

Wetland conservation and restoration is well supported in America (by the US Army Corps of Engineers and the Environmental Protection Agency through Section 404 of the Clean Water Act) (Kruckzynski 1990, National Research Council 1992). In comparison, recent initiatives in Europe (by the World Conservation Union Wetlands Program, the World Wildlife Fund for Nature, the International Waterfowl and Wetlands Research Bureau, and other nongovernmental organizations) need to be further strengthened to preserve wetland integrity. As stated above, one of the major problems that wetland managers are facing is the disap-

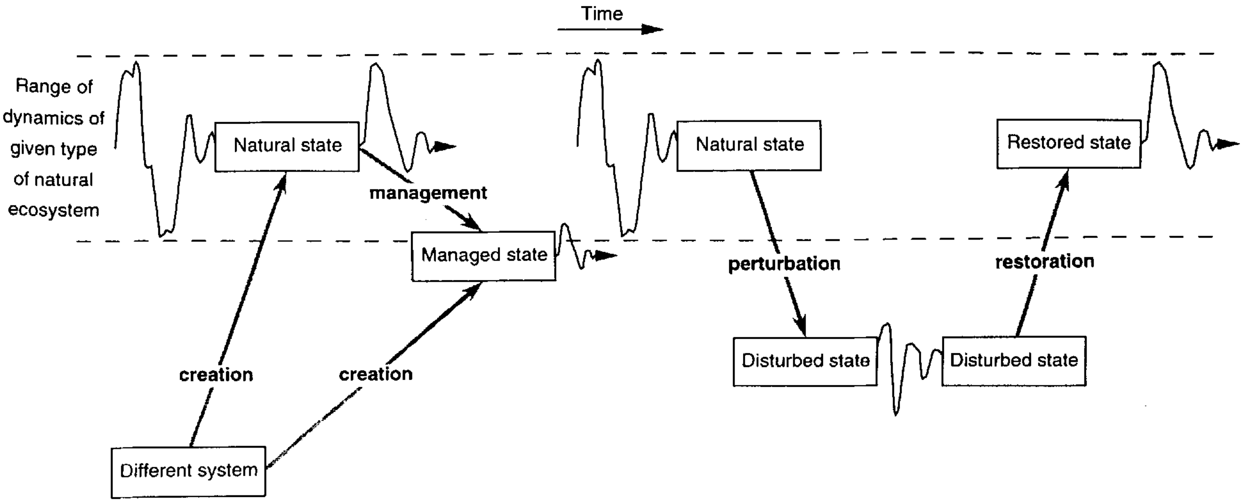

Figure 1. Natural and man-controlled or -induced ecosystem dynamics (inspired by Blandin and Lamotte 1985).

pearance of wetlands by terrestrialization. It is therefore necessary nowadays to focus on ecotechnologies (Berryman and others 1992) to restore selected ecosystems (Nelson and others 1989) in an attempt to induce regressive succession to return to conditions prevailing in the past.

Numerous works have been carried out on lakes, and several techniques to restore these ecosystems by sediment removal are widely known [for example, Peterson (1982) for American and Swedish lakes, Imboden (1992) for Swiss lakes, Møller (1992) in Denmark, or Driessen and others (1993) in the Netherlands]. These include increasing the depth and consequently the volume of the lake to increase fish production, removing nutrient-rich sediments, removing toxic materials, and decreasing abundance of plants. Work carried out on vegetated wetlands is more rare. In the present paper, the emphasis is placed on riverine wetlands and their restoration to focus on techniques used to reverse wetland eutrophication and terrestrialization and to propose to wetland managers a scientific framework for restoring riverine wetlands (particularly former river channels) using reversible processes to increase sustainability. Another important point is that the success or failure of a restoration project must be measured by long-term monitoring and by comparing restored ecosystem dynamics to a reference channel dynamics.

Restoration Projects in Riverine Wetlands: Some Examples

Several restoration projects have recently occurred in American large rivers. The main goals of these projects were flood hazard reduction and protection (Charles River, South Platte River, Kickapoo River, Wildcat and San Pablo creeks, Mingo Creek), restoration of water quality (Chattahoochee River, Big River), or creation of an offstreet nonmotorized transportation system (Boulder Creek) [further details in US Department of the Interior, National Park Service (1991) and in Robinson and Marks (1994) for Big River]. All these restoration projects include wetlands occurring in floodplains, because they can serve as natural reservoirs for floodwater, provide wildlife habitat and areas for outdoor recreation, and can help to maintain water quality. Only in rare cases was ecosystem (including wetlands) protection and restoration an important goal of the project (Big River or Wildcat and San Pablo creeks for example) or even the main goal (Kissimmee River). In the latter example, the main project goal was to restore lost environmental values of the original ecosystem (precanal ecosystem), taking into account the entire river system. This project demonstrates that many ecological values of the riverine–floodplain system can be restored if prompt and decisive action is taken by a competent, properly funded interdisciplinary team (Berger 1992). Maintaining and restoring wetlands was also an important component of the watershed protection strategy for the Mississippi River. In the Upper Mississippi River, particular attention has been paid to rectifying sedimentation problems in side channels and backwaters, through a combination of dredging and alteration of flow patterns by channel structures (Sparks 1992). It was among the first restoration programs in North America to address conflicting federal mandates for large interstate rivers and to redress habitat degradation caused by alteration within the rivers and their drainage basins. Concerning only American wetlands, but not always riverine ones, several restoration projects and numerous creation projects have been carried out to enhance water quality (Erwin 1990a). Restoration of degraded riverine and riparian habitats in the Great Basin and Snake River regions targeted several goals (including flood storage), but the success of these projects must be viewed over the long term. Many wetland restoration projects have been initiated only recently, and their success cannot be realistically assessed at this time (Jensen and Platts 1990).

Restoration schemes are planned or have already been completed at some sites taken into account by the Ramsar convention and other wetlands in Europe (Hollis and Jones 1991). For example, water pumps were installed to flood the marshes to compensate for reduced river and groundwater flow in Doñana National Park, Spain. This involves a permanent energy supply to control the ecosystem and thus corresponds to management rather than to restoration. In Sweden, 30% of the surface is composed of wetlands, lakes, and rivers. Numerous wetlands or former lakes are rapidly aging due to macrophyte invasion: *Phragmites australis* covers between 100,000 and 200,000 ha. Björk (1992) and Larsson (1994) have suggested solutions to restore shallow lakes and wetlands: raise the water level, lower the bottom of the lake, or combine these two measures. Under all circumstances they also recommend the cutting of macrophytic vegetation and destruction of root felt, using amphibious and pontoon machines.

Numerous pilot restoration projects have just started or will be carried out in floodplains in European countries [Austria, Belgium, France, Germany, Hungary, The Netherlands, Switzerland, United Kingdom; a synthesis can be found in Lammens and Marteijn (1992)]. The objectives of these projects are diverse because different interests can be brought together and depend on the river and its floodplain size and geomorphology. For example, various preliminary studies have been conducted recently, particularly by the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA), in large European rivers that have been channelized since the 19th century (Rhine, Meuse, Danube). Their restoration potential has been assessed considering ecological barriers, such as water pollution, that prevent full recovery of the floodplain in the short term (Botterweg and Kerkhofs 1994, Schoor 1994, Silva and Kerkhofs 1994, van den Brink and van der Velde 1994). The Rhine watershed is the most densely populated and polluted river basin in Europe. The Lower Rhine floodplain functions will be restored by removing some of the small summer dikes from the river to allow flooding between the permanent winter dikes. This area will be devoted to nature conservation, and its flooding should improve both the quality of the river water and the flora and fauna dependent upon it. Similarly, it is possible that the former floodplains in the Upper Rhine valley might be renaturalized and used for ecological protection against floods (Dister 1992, Obrdlík 1992), to enhance biodiversity and ecological diversity (Durrer 1992, Goetghebeur 1992), and to improve water quality (Carbiener 1992). A water diversion structure was proposed by biologists and ecologists to reconnect former Danube meanders in the headwaters of the Gabcíkovo–Nagymaros barrage system (Lisicky 1992).

In France, the Groupe de Travail "Valorisation Agronomique des Zones Humides" (1986) tried to propose new management techniques for wetlands, including ecological engineering if necessary. The aim of this working group, funded by the French ministries of agriculture and environment, was to preserve wetlands and develop them from an economic (agriculture) and social point of view. More recently, Pont and others (1992) and Michelot (1994) studied 20 French riverine natural parks located in the floodplains of large rivers. These protected areas include rivers of various geomorphology, former braiding and meandering channels more or less connected to the main channel, islands, estuaries, and freshwater ponds or marshes. All of them suffer from human impacts on rivers: spates are totally prevented or reduced in 90% of these reserves, and groundwater level had decreased in 70% of them. Almost all the managers of French riverine wetlands promote measures to counteract terrestrialization processes. They tried to control fluvial dynamics in some natural parks by increasing flooding duration and preventing erosion/sedimentation and/or riverbed incision. Water quantity and quality are also controlled in almost all the French natural parks by various means. Water levels are controlled or kept high by weirs and/or water pumps. In some cases (particularly in former river channels), the site is dredged to increase its water depth. Both former braiding and meandering channels have also been reconnected to the river or to tributaries at their upstream end to increase water supply. Numerous natural park managers also have tried to increase water quality by diverting polluted tributaries or by encouraging their purification.

Restoration experiments were often inappropriate and were followed by unforeseen problems, such as self-sustainability (if sedimentation processes are higher than erosion processes) and water-quality problems (particularly after reconnection of wetlands to the river). This is due to insufficient scientific investigation before restoration for evaluating the potential for suc-

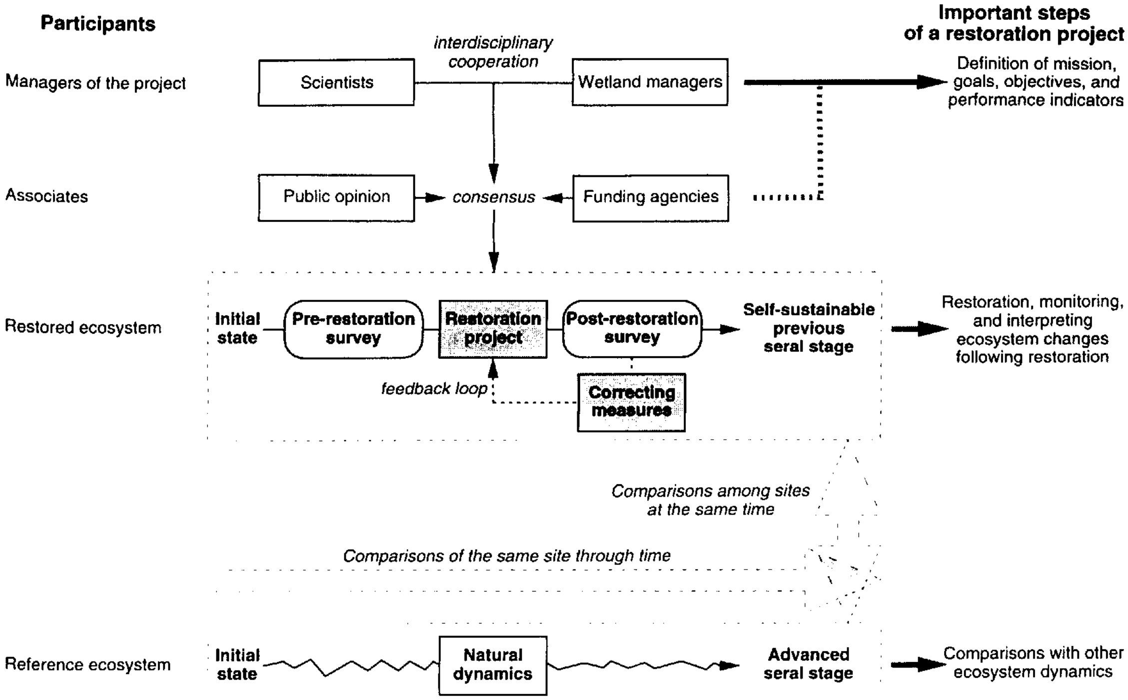

Figure 2. A scientific-based decision framework for restoration projects.

cessful execution of the project and unjustified motivations. Furthermore, natural park managers usually do not take into account the appropriate spatial scale to study and solve their problems. Therefore, they fight against problem symptoms rather than against their real causes. Restoration durability (persistence of the restored state) is thus generally low. The following water variables are not monitored in half of the French riverine natural parks: discharge; surface and groundwater levels and physicochemistry (including salinity); duration, frequency, and intensity of floods; and hydrobiological data.

How to Restore Riverine Wetlands Facing Terrestrialization

It is often difficult to know why restoration projects have failed or succeeded. For some restoration projects, success or failure can not be evaluated at all because of the lack of pre- and postrestoration monitoring of ecosystem changes. To increase restoration project success in the future, we need a reliable methodology. Thus, every experimental project should follow the framework proposed in Figure 2. This framework includes planning the project on a strong theoretical base to define appropriate goals, objectives, and performance indicators; pre- and postrestoration monitoring; and comparison with changes observed in other ecosystems.

Restoration Legitimacy

Ecosystem restoration and management requires a balancing of ecological, economic, and social considerations (MacKenzie 1993). Thus, an important aspect of restoration that every project should take into account is both its ecological or scientific legitimacy and its public and political legitimacy. Legitimacy is difficult to assess, but one test of a restoration project's legitimacy is the measure of the financing provided for the project by various institutions and agencies.

Ecological legitimacy. Scientific legitimacy is evident if the restoration project is effectively initiated and conducted (after a precise definition of the project mission, goals, objectives, and performance indicators) by an interdisciplinary team of scientists, focusing on ecological integrity (Odum 1994). The restoration project must be worked out by scientists in cooperation with, at least, the staff of the firm responsible for the technical side of the project (Björk 1992). If restoration is requested by the public (for example, by riverside inhabitants who want to restore a former river channel for fishing), scientists should be integrated as soon as possible in the project design to define appropriate goals, performance indicators, and monitoring.

Too often in the past, restoration projects (including wetland selection, project and monitoring design) have not been built upon a strong theoretical ecological base. Recent ecological concepts give a theoretical framework to increase restoration success, as well as to understand failures and to avoid them in the future. The ecotone concept (Naiman and others 1988, Naiman and Décamps 1990) or the riparian control concept (Conners and Naiman 1984) are complements of the river continuum concept (Vannote and others 1980) that assume that riparian forests influence the aquatic ecosystems. Riparian forests constitute a significant component of the riverine landscape, particularly important in agricultural watersheds (Vanek 1992). They increase the habitat diversity, act as a filter for diffuse water and mass inputs from the surrounding land, stabilize the shores, and may increase the shading of the stream channel preventing the proliferation of aquatic plants. These forests impart resistance and resilience to disturbance of adjacent patches and thus should be preserved or recreated during restoration of aquatic ecosystems (Loucks 1990, O'Sullivan and Wilson 1992). The connectivity concept can be applied to the hydrological connectivity of the river and its backwaters (including riverine wetlands) via surface water and groundwater at various water level stages. This is important for nutrient recycling, production, decomposition, sediment formation, and obstruction of the groundwater aquifer (Amoros and Roux 1988, Amoros 1991). As connectivity is important for recolonization after restoration, it can be increased by enhancing reversible successional processes (Amoros and others 1987a) such as fluvial dynamics. Connectivity can also be restored by direct intervention on reversible processes such as the alluvial deposition at the ends of former channels. As Gore (1985) pointed out, both for vegetation and fauna, most fluvial restoration projects entail the restoration of habitat, which is soon invaded by pioneering and then colonizing organisms if there are sources of species upstream, downstream, or in tributaries. In the same way, the flood pulse concept proposed by Junk and others (1989) assumes that the pulsing of the river discharge, the flood pulse, is the major force controlling biota in river floodplains [examples on aquatic vegetation in Henry and others (1994 and 1995a)]. The flooding frequency is a particularly important predictor of the potential for vegetation development after restoration (Lammens and Marteijn 1992). Natural processes like floods tend to take a long time but are less expensive and may be longer lasting than artificial methods that may give more immediate results. Meanwhile, restoration of the flow regime is one of the most neglected aspects of stream and river restoration (National Research Council 1992). Restoration should thus take river dynamics into account by allowing enough spatial and temporal scope for natural processes, including floods, to occur and act on extrinsic forces (for example promoting disturbances) to change the intrinsic wetland elements and modify succession (Willard and Hiller 1990). The projects should aim to restore hydrological disturbance as well as groundwater supply, to maintain a self-sustainable state after restoration by preventing siltation (Bornette and others 1994) and increase biodiversity [examples on aquatic vegetation in the Rhône River former channels in Henry and others (1994 and 1995a)]. Furthermore, as water quality is degraded in most of the large rivers, it is important to not directly supply the restored wetland with river water but to favor a generally better quality groundwater supply.

Public legitimacy. The public has become increasingly aware of the need for restoration of river–riparian ecosystems. Numerous public agencies, private organizations, and citizen groups (local inhabitants or landowners) are subsequently likely to initiate further stream and river restoration projects. Conversely, the public needs and wants to be better informed about the rationales, goals, and methods of aquatic ecosystem restoration. Consequently, restoration project design must be prepared by scientists but discussed with all people concerned, through open forums as suggested by Denny (1992).

Financing. As stated by MacKenzie (1993) for the Great Lakes management programs, suport for restoration projects is challenging because politicians prefer to support programs that can demonstrate visible and rapid achievements. As was too often the case, financing must not only be provided for the restoration project but should also include preproject documentation. To evaluate the long-term success of restored ecosystems, financing must also be provided to guarantee long-term maintenance and monitoring of the project (National Research Council 1992). Adequate financing will and should be provided for restoration projects based on rigorous science and conducted by highly qualified participants (including natural and social scientists, public and private sectors, and policy makers) (MacKenzie 1993).

Restoration Goals and Performance Indicators

Planning a restoration project must start with specifying the project mission, goals, objectives, and performance indicators (Lewis 1990, Björk 1992, Lammens and Marteijn 1992, National Research Council 1992, Ward 1992). The goal of any wetland restoration project should be to restore a dynamic equilibrium impeding the terrestrialization processes. The objectives derived from these goals could be, for example, to expose coarse sediments for increasing groundwater supply, which would lead to reduced nutrient levels and to reduced proliferation of vegetation. To develop the correct objectives and performance indicators to properly measure the success or failure of a restoration project, this step should be carried out by an interdisciplinary team of scientists [including for example ecologists and hydrologists; (Schiemer and Janauer 1994)], but restoration will and should also develop in a dialog between scientists and engineers who are open to the topic (Cullen 1990, McCutcheon and Walski 1994, Mitsch 1994, Odum 1994). Various performance indicators should be defined accurately and reliably to measure ecosystem changes and thereby to assess progress toward the project's mission, goals, and objectives (National Research Council 1992, Denny 1992, Schiemer 1994). To obtain information on different aspects of the studied ecosystem functions, various physical, chemical, and biological variables can be used as "describers of functioning and dynamics" of complex systems (Bournaud and Amoros 1984, Amoros and others 1987b) or "limnological indicators" (Schiemer 1994). These variables, also called "vital ecosystem attributes" (Aronson and others 1993), should describe both ecosystem structure (does the restored ecosystem look like the desired ecosystem?) and ecosystem function (does the restored ecosystem behave like the desired ecosystem?), even if functional performance is more difficult to assess than ecosystem structure (National Research Council 1992). According to Schiemer (1994) and Schiemer and Janauer (1994), it is impossible to recommend a fixed scheme of variables to monitor at present due to the complexity of floodplain ecosystems and because the importance of parts of the list of variables will vary, depending upon the reasons for restoration (Ward 1992). Meanwhile, to test if ecosystem changes after restoration correspond to the project's mission, goals, and objectives, Table 1 indicates some of the performance indicators that can be used. As shown in this table, the performance indicators should not be restricted to only one level of biological organization. Kentula and others (1992) and Ward (1992) recommend the monitoring of at least one variable measuring each of the three parameters (wetland hydrology, hydrophytes, and hydric soils) that indicate the presence of a wetland. The overwhelming majority of the projects considered as successful in a US Environmental Protection Agency report (Kusler and Kentula 1990) were judged only on the basis of vegetation establishment. Neither the wildlife present nor the functional capacity (for example, hydrologic functions, water-quality improvement, food-chain support) of the ecosystems were taken into account in evaluation for the simple reason that data were not available. The performance indicators should and must be measured in various ecosystem compartments or elements and at various spatial and temporal scales (Schiemer 1994, Janauer 1994) because they give complementary information at different spatial (De Mars and Wassen 1993) and temporal scales. For example, considering only fauna (Schiemer 1992): among macroinvertebrates, aquatic mollusks and water beetles are linked to small-scale aquatic habitats (for example, Foeckler 1990); fish require littoral spawning sites, and some species change their habitat requirements in the course of their life cycle (for example, Schiemer and others 1991); and other groups (such as heterotopic aquatic insects, amphibians, or aquatic birds) require different combinations of both aquatic and terrestrial habitats. From a temporal point of view, surficial sediments and vegetation describe changes at the scale of one or several years, macroinvertebrates and fishes—highly mobile—are sensitive to more rapid processes (seasonal scale), and water quality gives nearly instantaneous information.

Monitoring

Project managers and designers should propose a monitoring and assessment program that is thus appropriate in spatial scale as well as in sampling frequency and intensity to measure the performance indicators. It must take into account the scale of the information given by each performance indicator (Janauer 1994, Schiemer and Janauer 1994).

Prerestoration monitoring. Where possible, in the case of a recent perturbation or if the perturbation was foreseeable (for example, when an hydroelectric scheme is designed on a river, if a study is ordered to get a precise floodplain ecosystems state prior to scheme construction in order to measure consecutive changes of floodplain structure and function), a precise preperturbation evaluation of ecosystem state allows us to define restoration project design and the desired state after restoration (Erwin 1990b) (Figure 1). If ecosystem perturbation is older, ecosystem state prior to perturbation could be approached using old aerial photographs and maps, historic records, or soil core samples. In the latter case, it may be impossible to reproduce, after restoration, the preperturbation state due to hydrologic, water-quality, and sediment regime changes in most rivers. Whenever perturbations occurred, appropriate prerestoration monitoring of the altered ecosystem state to provide baseline data, the basis for the technical design and execution of the restoration project, should be conducted over at least one year (Björk 1992). The impor-

Table 1. Some performance indicators related to ecosystem structure and function

General characteristics	Water and/or sediment	Vegetation	Fauna (invertebrates and fish)
Hydrology	Physicochemical variables	Annual and perennial species richness	Richness, density, and diversity
Topography	Groundwater supply	Ratio of hydrophytes/ helophytes	Keystone species
Morphology	Floodwater and sediment retention	Total plant cover	Biomass productivity
Energy flow	Nutrient availability and cycling	Above- and underground phytomass	Transport of organisms
Local climate	Organic matter	Alpha and beta diversity	
	Soil and geological condition	Life form spectrum	
	Sedimentation rate	Keystone species	
	Soil biota diversity	Phytomass productivity	
	Microbial biomass	Transport of organisms	

tance of baseline or reference data for evaluating restoration success or failure was pointed out by the National Research Council (1992). Reference data, issued from a similar ecosystem carefully chosen considering both its structure and function, should be used for comparisons among ecosystems at the same time and may represent either the ecosystem state before restoration or the desired ecosystem state after restoration. In the former case success or failure of the restoration project will be measured by how far the ecosystem moves from the altered state, whereas in the latter case it will be measured by how the restored ecosystem resembles and functions like the reference one. In some rare cases, when similar restoration projects have been carried out on similar ecosystems in the same region, data may also be available for comparisons with actual and future ecosystem changes after restoration (Kentula and others 1992). As already stated, long-term and well-designed monitoring using both baseline and reference data should increase our understanding of ecosystem changes after restoration.

Postrestoration monitoring. Postproject evaluation of wetlands is a key element, but it is seldom performed (Brooks 1990, Kusler and Kentula 1990, Larson 1990, Kentula and others 1992). It constitutes a necessary step to enable scientists to determine when and to what degree the system has become self-maintaining and whether or not the restoration attempt was effective (National Research Council 1992), but, as stated by Fairweather (1993), monitoring is a waste of everyone's time and money unless appropriate action is taken, via a feedback loop, to correct the restoration project, particularly if the ecosystem state after restoration does not correspond to the desired state or if new problems emerge because something unplanned happens (Zedler and Weller 1990, Kentula and others 1992).

Monitoring duration after restoration. Some restored ecosystems have been monitored for a short time; less have been monitored over the long term (Kusler and Kentula 1990). Furthermore, numerous restoration projects have been judged successful after a short time, but demonstrate partial or total failure (generally, a rapid ecosystem degradation towards prerestoration state) several years after restoration (Ward 1992), especially if there is no active management of hydrology (Larson 1990). Long-term monitoring after restoration is therefore necessary to assess and understand success or failure of restoration projects. Monitoring should be long enough to document a self-sustainable state after restoration. Whereas invertebrate or fish reestablishment should be rapid after restoration (a few months), vegetation reestablishment may take more than one year. Thus, postrestoration monitoring should be precise and intensive during, at least, the first two or three years (numerous regular surveys). It can be continued at a lower frequency thereafter, with reevaluation occurring at 5-, 10-, or 15-year intervals (Zedler and Weller 1990, Kentula and others 1992). The latter will enable detection of events that may influence ecosystem changes over time (man-induced undesirable changes, cyclic changes of varied frequencies, successional trends, and unpredictable rare events that may be of great ecological importance) (Husák and Krahulec 1994).

Conclusion: General Recommendations and Research Needs

As the water quality of rivers declined and because of channelization, many freshwater wetlands have been altered. Thus, numerous opportunities to restore them exist. The practice of restoration must, however, move from a trial-and-error process to a predictive science. We need to know what ecosystem functions can be restored under various conditions and how rapidly restoration can proceed. There should be ways to speed up the development of ecosystem functions in restoration sites, thus shortening the time required to attain the desired dynamic equilibrium.

First, project managers and designers must always strive to restore wetlands to self-sustaining ecosystems requiring minimal maintenance. However, the flood pulse concept contrasts sharply with the concept of stabilizing a stream channel to avoid loss or damage to structures or agricultural fields. Therefore, the goal of fluvial restoration should be to restore the river or adjacent wetlands to a dynamic equilibrium, not to stabilize a channel or bank as has been done too often in the past. We must also develop innovative methods of accelerating the restoration process (Henry and others 1995b) and establish regional, national, and international data bases to provide comparisons of the natural functioning of different wetland ecosystem types in different regions. Scientists must design and conduct experimental research programs to examine wetland restoration techniques and functional development over time in different system types. These experiments could use comparisons of different wetland types among regions and at different stages of development, including both restoration projects successes and failures.

Finally, as the basic science of restoration is ecology, restoration and ecosystem creation will be the ultimate "acid test" of our understanding and of many ecological theories (Bradshaw 1983, Cairns 1988b, Mitsch 1993). Ecological engineering starts with one of the more extensive science bases available, which, along with ecosystem analysis, provides the rigorous quantitative means to understand the common nature of ecosystems as well as the natural variability (McCutcheon and Walski 1994). Both the success and failure of restoration projects will expose strengths and weaknesses of theories, but this requires long-term monitoring and reporting of the results and of the techniques being used in scientific journals.

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