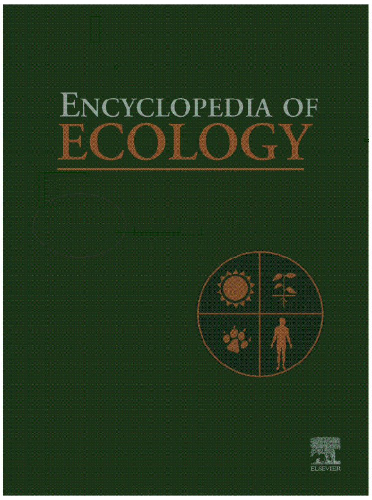

J N Murdock. Stream Restoration. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), Ecological Engineering. Vol. [4] of Encyclopedia of Ecology, 5 vols.
pp. [3390-3397] Oxford: Elsevier.

See also: Erosion; Lake Restoration Methods; Landscape Planning; Material and Metal Ecology; Nitrogen Cycle; River Models; Rivers and Streams: Physical Setting and Adapted Biota; Stream Restoration; Water Cycle.

Further Reading

Benke AC and Cushing CE (eds.) (2005) *Rivers of North America*. Amsterdam: Elsevier.
Dodds WK (2004) *Freshwater Ecosystems: Concepts and Environmental Applications*. San Diego, CA: Academic Press.
Drinan JE and Spellman FR (2001) *Stream Ecology and Self-Purification: An Introduction*, 2nd edn. Landcaster, PA: Technomic.
Harper DA and Ferguson JD (eds.) (1995) *The Ecological Basis for River Management*. Chichester: Wiley.
Hauer FR and Lamberti GA (eds.) (1996) *Methods in Stream Ecology*. San Diego, CA: Academic Press.
Junk WJ, Bayley PB, and Sparks RE (1989) The flood pulse concept in river flood-plain systems. In Dodge PP (ed.) *Proceedings of the International Large River Symposium, Special Publication. Canadian Journal of Fisheries and Aquatic Sciences*, vol. 106, pp. 11–127.
Kangas PC (2004) *Ecological Engineering: Principles and Practice*. Boca Raton, FL: Lewis.
Leopold LB (1994) *A View of the River*. Cambridge, MA: Harvard University Press.
Mitsch WJ and Jorgensen SE (eds.) (2004) *Ecological Engineering and Ecosystem Restoration*. Hoboken, NJ: Wiley.
Schulze PC (ed.) (1996) *Engineering with Ecological Constraints*. Washington, DC: National Academy Press.
Vannote RL, Minshall GW, Cummins KW, Sedell JR, and Cushing CE (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 130–137.
Ward AD and Trimbal SW (2004) *Environmental Hydrology*, 2nd edn. Boca Raton, FL: Lewis.
Wetzel RG (2001) *Limnology: Lake and River Ecosystems*, 3rd edn. San Diego, CA: Academic Press.

Stream Restoration

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Ecological Stream Restoration
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Introduction

Stream restoration is the re-establishment of a stream to a state that is more reflective of its predisturbance form. Although many projects that are referred to as restoration have endpoints designed to mitigate negative anthropogenic (human) effects, not all have a goal that focuses on the ecological health of the system. For example, a stream with extensive aquatic plant and algal growth caused by cultural eutrophication may be restored with the goal of increasing recreational opportunities on the stream, but not necessarily a return to the native condition. Stream structure and function may be improved by reducing nutrient loading; however, plans could also include aspects that have a negative ecological effect such as controlled flows to maintain navigable water, or construction of visitor parking lots and buildings on riparian areas.

Ecological stream restoration focuses on restoring and/or improving stream ecosystem structure and function, that is, on improving the ecological integrity of the system. This holistic approach encompasses the physical, chemical, and biological components of a stream ecosystem and ideally leads to a self-organizing, self-purifying, and more resilient system that will ultimately require minimal management and cost less to implement and maintain. In ecological restoration, the return of predisturbance ecosystem components and their functions are emphasized, including biodiversity, and nutrient cycling and retention, as well as overall intrinsic value. In addition, social, economic, and health benefits (e.g., pollution reduction, ecotourism, recreation, and flood control) frequently accompany enhanced ecological integrity. Many political, social, and economic requirements are considered when designing stream restoration projects, and often many stakeholder groups are involved in a single project. These requirements can greatly complicate successful ecological restoration and must be considered to develop a successful plan. However, this article focuses only on the ecological aspects of stream restoration.

Ecological Engineering and Stream Restoration

Ecological engineering incorporates contemporary environmental engineering practices with ecological principles to attain ecologically driven goals. Ecological engineering is defined as the design, restoration, or creation of ecosystems, with a strong emphasis on ecosystem self-design and self-organization. When using ecological engineering to restore a system, often less effort is needed, or desired, to begin ecosystem recovery due to the self-designing qualities of this approach. Stream conditions are designed to mimic the predisturbance environment and incorporate not only physical parameters such as channel dimensions and hydrologic variation, but also include species composition manipulation and water quality. Once these initial conditions are implemented, the system is left to organize itself. The basis for this approach is that the biotic component will organize itself through community interactions such as competition, predation, etc., to establish the most stable and energy-efficient system for the environmental conditions in the stream. Essentially, if the abiotic template is restored, conditions under which the native community evolved will exist and native organisms will be favored to dominate the system without input of additional effort. See Stream Management for further information on the basic principles of ecological engineering.

The focus of ecological engineering and ecological restoration is similar. Both strive for ecosystem functioning and biotic resilience from disturbances comparable to the historic conditions through the creation of the most natural system obtainable. Resilience is the ability to return to the original state after a disturbance. In streams, disturbances are a natural part of the ecosystem, as floods and droughts shape the physical aspects of the channel and the development of native communities. Thus, native species abundances often quickly return after a natural disturbance and are said to be very resilient. However, recovery from anthropogenic disturbances such as channelization, chemical contamination, or cultural eutrophication often provides a different starting point for native species recovery. Instead of native species colonizing a 'bare' system, recovery occurs with a shift in dominance from pollution-tolerant species to pollution-sensitive species. The distinction between resilience to natural and anthropogenic disturbances is important because a pollution-tolerant community may be more resilient to a natural disturbance in the presence of human-caused disturbances, which may be the reason these pollution-tolerant species have taken over.

In addition, both ecological engineering and ecological restoration stress on minimal human maintenance and continued interference. To correctly identify the best ecological engineering approach to use for a given restoration situation, is it imperative to understand the ecology of the stream.

Ecological Stream Restoration

Restoration Goals and Strategies

The goal of ecological stream restoration is to restore the stream ecosystem's physical, chemical, and biological composition to its native state. Ecological stream restoration includes restoring the natural physical and biotic dynamic nature and species diversity, which leads to increased functionality in regard to energy flow and nutrient cycling. In its purest sense, stream restoration strives to achieve the most natural system possible in a given area. In most areas of the world, this means returning the stream to a pre-industrialization form. In North America, restoration goals typically attempt to reach pre-European settlement form. There are several intrinsic problems with this approach, the most obvious being that the parameters of the system before anthropogenic alterations are difficult to determine. If the parameters are known, there may be little chance that these stream conditions could be realistically reached without completely removing all human influence from the watershed. The problem of unrealistic recovery goals has led to the use of more defining terms for restoration such as rehabilitation and recovery, which imply restoring the stream as close as realistically possible to the predisturbed state.

The term stream restoration is also different from stream management. Restoration is a type of stream management (although more restrictive), and is differentiated by its goal to bring the system to a more natural state (although many do have alternative incentives), while management goals can be broader and could include more socially or economically driven targets. Many of the same strategies used in stream restorations are implemented in stream management projects, for example, environmental engineering, conservation, adaptive management, as well as ecological engineering. Stream management practices frequently require a more immediate response necessitating greater effort, as management often addresses certain stream aspects that must be dealt with in a timely manner and directly affect human activities, such as flood control and drinking water quality issues.

When implementing ecological restoration, results often take more time to appear, for example, several generation times for species of interest. The cost and effort applied to both management and restoration projects are extremely variable and project specific; however, the use of ecological engineering may reduce costs for both types of projects. A common ecological approach is to eliminate or reduce a pollutant or human disturbance and let the ecosystem recover on its own with minimal human interference. In the long run this approach may be the most cost-effective and ecologically sound, as there is minimal collateral damage to the stream ecosystem during restoration activities. For instance, damage to riparian and floodplain habitat by large equipment during physical channel modifications, or near stream pump and treat groundwater decontamination activities can be avoided.

As in most stream modification projects, the design and monitoring phases of restoration are critical. Although the restoration of lotic systems has been occurring around the world for many decades, a standard set of criteria has not been established. Criteria can differ depending on the basic approach used (e.g., ecological vs. environmental), the goals sought (e.g., flood control vs. native fish recovery), and the site-specific climactic and geologic conditions. Since ecological restoration has a unifying defined goal, to reach the native ecosystem state, certain criteria can be universally applied. Restoration measures include, but are not limited to the following:

1. Ecological-based goals that strive to achieve a more stable, resilient, and natural system.
2. Collection of prerestoration data to establish a known ecological starting point.
3. An attempt to understand and address basic stream ecosystem processes and interactions, including site-specific and season-specific interactions between ecosystem components. This understanding is critical to reduce the potential of unintended ecological responses to restoration activities.
4. A postrestoration monitoring program implemented to determine if ecological integrity has improved, and continues to improve with minimal human maintenance. Restoration monitoring is an important aspect of the process. However, determining which aspects of the project provide the best estimate of progress must be carefully decided, and will most likely depend on site conditions and restoration goals.
5. Minimize damage to the stream while performing restoration activities.

Ecological Challenges

Stream restoration has many ecological challenges that are unique to lotic (flowing) ecosystems. Streams are constantly changing environments and can be thought of as being in a state of dynamic equilibrium. This increases the difficulty of predicting how various ecosystem components will react, and can change interactions on relatively short timescales such as after large floods. Unknown or unexpected ecological responses to particular actions can occur despite adequate site research and planning. Also, determining restoration potential can be difficult, because finding nearby reference streams with minimal human impact may be impossible.

Stream restoration occurs at many spatial scales, and scale-associated factors must be considered when designing restoration actions. Stream order, a hierarchical size classification system where streams are grouped in relation to tributary size, is critical as ecological relationships between organisms and their environment can change across stream sizes. In addition, human activities have varying effects on streams of different orders, due to differences in dilution capacity and water/sediment contact time. Since channel size is frequently related to watershed size, stream order provides additional restoration challenges. Larger watersheds regularly contain more sources of pollution and permanent human alteration such as urban development, sewage/industry outfall, cultivated land, and nonpoint pollution runoff. These increased pollution sources reduce the ability to mitigate all negative influences on ecosystem integrity. Permanent watershed alterations also limit the restoration potential of a stream, as their negative impact cannot be completely mitigated. An additional scale issue concerns the size of the restoration project. Whether the project encompasses a pool, reach, segment, watershed, etc., changes the necessary approach (Table 1). Larger projects must often take into consideration tributaries and groundwater input, a greater impact from atmospheric deposition, and problems due to the stream flowing through multiple geographic and political boundaries.

Stream Ecology and Threats to Ecological Integrity

Ecology is the study of interactions among living organisms and their environment. In every ecosystem, species

Table 1 Examples of ecological stream restoration of different scales

Pool/riffle/reach	*Segment/basin*
Add/modify instream habit	Restore stream sinuosity
Add/remove riparian vegetation	Restore connection with floodplain
Remove invasive species	Remove flow constrictions (dams, levees)
Reintroduce native species	Reduce sediment input (landscape scale)
Remove/reduce pollution point source	Reduce nutrient input (landscale scale)

Table 2 Major human source of nitrogen and phosphorus

Source	*Main forms (D = dissolved, P = particulate)*	*Transport mechanisms*
Agriculture		
Animal (waste)	$NH_{4\,(D,P)}$, $NO_{3\,(D)}$, $PO_{4\,(P)}$	Runoff, groundwater, direct animal defication
Cropland (fertilizer, sediment)	$NO_{3\,(D)}$, $PO_{4\,(P)}$	Runoff, groundwater
Urban/suburban		
Sewage disposal/septic systems (effluent, sludge)	$NH_{4\,(D)}$, $NO_{3\,(D)}$, $PO_{4\,(D)}$	Direct discharge, groundwater
Lawns/golf courses (fertilizer)	$NO_{3\,(D)}$, $PO_{4\,(D)}$	Runoff, groundwater
Construction/land clearing (sediment)	$PO_{4\,(P)}$	Runoff
Automobiles (fossil fuel combustion)	$NO_{3\,(P)}$	Dry deposition, rain, snow
Industrial		
Liquid/solid waste discharge (multiple)	$NH_{4\,(D,P)}$, $NO_{3\,(D,P)}$, $PO_{4\,(D,P)}$	Direct discharge, runoff
Atmospheric discharge (multiple)	$NO_{3\,(P)}$	Dry deposition, rain, snow

composition and abundance at every level, from primary producers to top consumers to decomposers, are regulated by environmental (abiotic) conditions. Compared to most other aquatic ecosystems, stream environments are more dynamic and characterized by nonequilibrium conditions. When compared to small streams, larger streams and rivers are typically more stable in regard to discharge, chemical composition, and community structure. However, smaller streams have been studied much more and can be manipulated more easily and usually at lower cost. Therefore, restoration plans often differ with stream size, even though they may be mitigating the same human activity.

The fundamental ecological interactions among components are very important because knowing how ecosystems are likely to respond to each restoration action is key to the success of a restoration program. Ecological stream restoration depends on understanding the physical, chemical, and biological constraints on developing stream communities that are predictable, and uses these relationships as a starting point for restoration design. There are, however, many uncontrollable variables that may alter these interactions and produce unintended results from restoration activities, and unaccounted for interactions may unintentionally degrade ecosystem integrity further.

The major physical factors that regulate stream ecosystems include hydrology (the daily and seasonal pattern of a stream's discharge), geomorphology (development and subsequent changes of a channel's physical dimensions over time), temperature, and light availability. Chemical components of streams that are often important in restoration projects include nutrients (mainly nitrogen and phosphorus) (**Table 2**), metals (mercury, lead, copper, cadmium, zinc, selenium, and arsenic), acidity, salinity, pesticides, and organic compounds (DDT, PCB's, PAH's, and ecoestrogens). The article Stream Management examines each of the above factors and their relationship to stream ecology in more detail. In addition, it lists major anthropogenic pollution sources and activities associated with these factors, and some basic, direct consequences of component alterations on stream ecosystem structure and function. These physical and chemical components shape the biological component of the ecosystem by regulating individual populations and whole community dynamics both during stable environmental conditions and after disturbances.

Biological succession is a fundamental process in ecological restoration. Succession is the process through which ecosystem biota develop over time, and is regulated by the order and rate that species colonize and grow in a new or disturbed habitat. The successional concept in restoration can encompass either the entire biotic community (primary producers to top predators), or individual species within a single group such as fishes or algae. Early successional communities (*r*-strategists) are defined by fast reproduction, short life spans, and low competitive ability. Over time, *K*-strategists become the dominant species. These species are defined as having slow reproduction, long life spans, and high competitive ability. In stream ecosystems, succession naturally occurs on a large scale after disturbances such as floods and droughts. Anthropogenic disturbances also lead to a loss in native species richness and abundance (**Figure 1**). A central goal of ecological stream restoration is to return native species, either through direct planting or introductions, or through natural migration and colonization from nearby sources.

Ecosystem Component Interactions

Many factors have a direct relationship to other environmental components while others are more complex and can complicate restoration actions. Direct and indirect

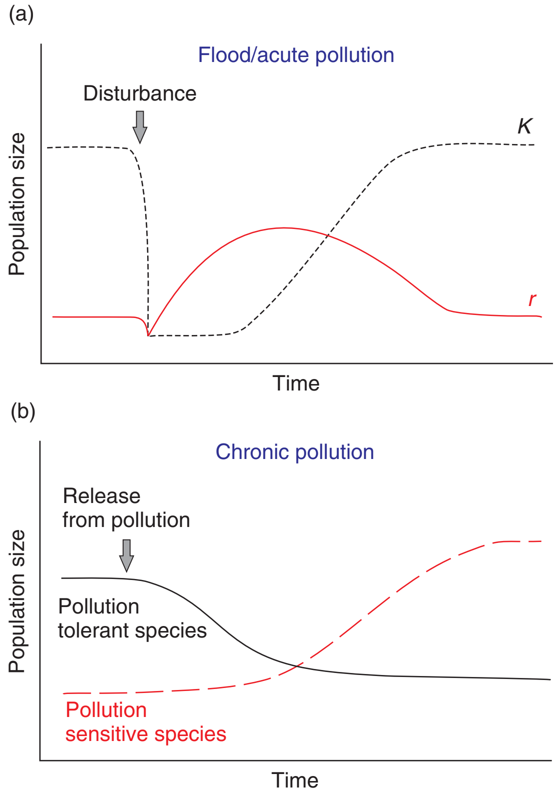

Figure 1 Examples of benthic algal succession from acute and chronic disturbances. (a) Disturbances such as floods or chemical spills can quickly remove viable algae from the stream. Once normal environmental conditions return, fast-growing *r*-strategist species flourish in a low-competition environment. Over time slower growing but more competitive *K*-strategist species accumulate and eventually dominate late successional assemblages. (b) Chronic pollution leads to a dominance of pollution-tolerant species with few to no sensitive species present. Reduction or alleviation of the pollution source allows a more natural assemblage to gradually return. These general patterns can be applied to organisms at all trophic levels; however, population susceptibility to the disturbance and recovery time will vary among organisms.

interactions can vary temporally and spatially as environmental conditions in the ecosystem change. Alterations of a particular component, whether by pollution or by restoration actions, often have both positive and negative affects on other ecosystem components.

Understanding how organisms respond to their environment (i.e., the ecology of streams) is critical to implementing a successful restoration project. It should be clear that specific restoration goals, cannot be addressed solely by a direct attack on the observable problem.

Some of the challenges in ecological restoration can be illustrated by data from Carter Creek in central Texas, USA. This is an urban stream heavily influenced by wastewater effluent. A continuous source of nutrients and clear water from multiple municipal wastewater outfalls increases instream primary production and light penetration which greatly increases benthic algal biomass and diurnal oxygen fluctuations throughout the year. The Carter Creek watershed is highly developed with approximately 70% covered by impervious surfaces and urban drainage systems that greatly increase watershed runoff. This scenario, along with a sandy streambed, results in a high frequency of algal scouring events that severely limits algal biomass standing stock (Figure 2). This also keeps algal assemblages in an early-successional and more edible form for grazers. Ecological restoration of streams is based on component interactions, and depends on predicting how a change in one component will affect other components in the system.

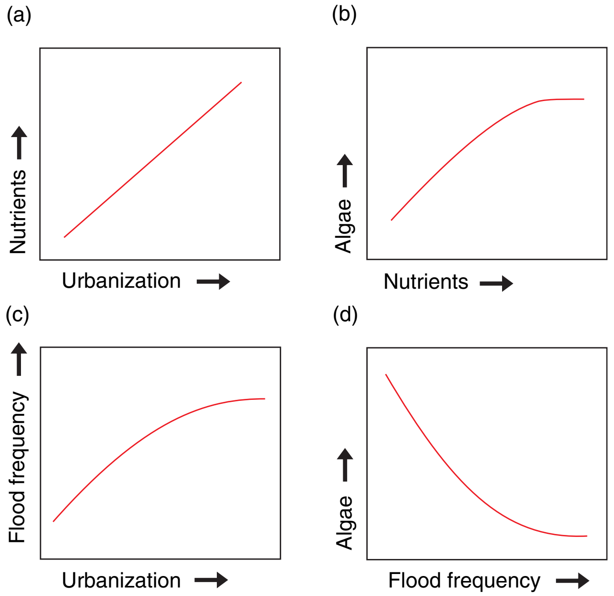

Figure 2 An example of physical, chemical, and biological component interactions. (a) Increased urbanization causes increased nutrient loading with no saturation affect. (b) Increased nutrients lead to increased algal growth; however, once nutrients become nonlimiting algal growth levels off. (c) Further urbanization leads to a higher frequency of flood events capable of scouring algae and flushing it out of the system. (d) Urbanization should reach a point where it no longer increases flood frequency and if scouring floods occur too often, significant algal growth may not be sustainable.

Examples of Ecological Stream Restoration

The Kissimmee River, Florida

The Kissimmee River in southern Florida, USA, is currently undergoing a major long-term, large-scale restoration process to reverse channelization that occurred more than 40 years prior. The river flows south from Lake Kissimmee

Figure 3 Aerial view of the channelized Kissimmee River, FL, USA. Photo courtesy of Pat Lynch, SFWMD.

to Lake Okeechobee, draining approximately 6200 km^2. Between 1962 and 1971, the river was straightened by dredging a channel through the Kissimmee River valley to prevent flooding in the developing watershed. Two-thirds of the historical floodplain wetlands were drained. A series of water control structures were created which regulated the flow of the river and created five sequential pools encompassing the entire length of the river. This enormous undertaking changed a 166 km river with a 3–5 km wide floodplain into a 90 km long, 100 m wide, and 9 m deep channel (Figure 3). This channel became known as the C38 canal and was considered an engineering marvel and success. Flooding was greatly reduced and new land was made available for development. Not long after the completion of C38 however, the effect of this project on the river and adjacent wetland ecosystems became apparent. Numerous restoration studies were undertaken during the next 20 years.

The creation of the C38 canal had greatly altered the physical, biological, and chemical components of the Kissimmee River ecosystem. The change in channel morphology along with the water control structures changed the seasonally fluctuating hydrology of the river, eliminating the regular floodplain inundation, and creating a more stable lentic aquatic habitat. Ecosystem changes were not limited to the river valley itself as the project destroyed 12 000–14 000 ha of adjacent wetlands. These physical alterations had unintentional cascading effects on the biological and chemical component of the ecosystem. Wintering waterfowl, wading bird, and game fish populations declined. Certain beneficial ecosystem functions such as nutrient retention from water draining into Lake Okeechobee (which was already experiencing elevated phosphorus loading) declined as well.

In 1976 the Florida legislature enacted the Kissimmee River Restoration Act that proposed a restoration of 69 km of river channel and 11 000 hectares of riparian wetlands, allocating approximately $500 million for the project (eight times the cost of the initial channelization project). The complete restoration plan is projected to take more than 15 years to complete. Restoration will consist of raising water levels to inundate the riparian wetlands through the existing water control structures in the upper basin, backfiling the canal, and creating new river channels in the lower basin. The goal of this restoration project is to return a significant portion of the Kissimmee River to its historic riverbed and floodplain and re-establish an ecosystem that will support the fauna and flora that existed prior to the creation of the C38 canal. The premise is that the re-establishment of natural water levels and flow will provide the habitat template and driving force for the restoration of ecological integrity.

A demonstration project was conducted in the 1980s to assess if restoring a natural flow regime to the historic river channel would improve ecosystem integrity, and if it was even feasible to keep the newly deposited channel sediment from washing downstream. This study involved inserted weirs into a section of C38. As expected, the weirs increased flow into the floodplain and historic channel, causing an increased transport of organic matter from the floodplain into the river channel, and also re-established more natural sand substrata in the river channel. Sediment loss issues were addressed through hydraulic modeling simulations.

Due to the magnitude of this restoration effort, feasibility studies were performed to assess the ecological impact of the restoration process itself. In 1994 a small (330 m) test area of the canal was backfilled and river water quality (turbidity, dissolved oxygen, mercury, and nutrients) was monitored for detrimental effects of the restoration process. No lasting effects of the effort were found. From 1999 to 2001, phase I of a four-phase project was completed. Twelve kilometers of the middle ‘pool’ of C38 were backfilled using 9.2 million cubic meters of Earth that was excavated during the original canal project. Two new river sections (2.4 km total length) were created to connect the original Kissimmee River channel, because portions of the historic channel were filled with spoil, or dredged through during the creation of C38. In addition, one of the water control structures was removed. This phase re-established flow through 24 km of the river. During this restoration process, river water quality was monitored for phosphorus, turbidity, and dissolved oxygen concentrations, and again no lasting detrimental effects on water quality were observed. It is unlikely that the entire river channel will be restored due to increased development in the basin since the C38 canal was created. Additional projects in the northern basin are underway to control both the flow of water and nutrient load down through the restored Kissimmee River valley.

This ecologically based project aims to restore both the structural and functional integrity of this river system.

An ecological evaluation program has also been created to track the restoration of the river and the floodplain wetlands. This program will follow physical, chemical, and biological components, and will allow for adaptive management opportunities to adjust the restoration process as needed to maximize the recovery of ecological integrity. Some of the variables that will be tracked include wading bird population numbers (biological), area of wetlands (physical), and miles of river with improved dissolved oxygen concentrations (chemical).

The Skjern River, Denmark

Conducting one of the largest stream restoration projects in Northern Europe, Denmark restored the natural channel morphology of the lower Skjern River. From 1962 to 1968 the lower Skjern was channelized and diked, and 4000 ha of adjacent wet meadow was drained and converted into arable land. Eliminating the meanders in the river, significantly reducing the total length, and eliminating the river floodplain interaction greatly altered the physical structure of this ecosystem. In turn, both biological and chemical components of this river/wetland ecosystem were negatively affected. For example, spawning habitat for Atlantic salmon was reduced and waterfowl populations decreased. Nutrient and sediment loads from agricultural fields and fish farms, and ochre (iron oxides that are toxic to aquatic organism) transport from drained meadows, into Ringkøbing Fjord increased. In addition, the drained land was subsiding due to loss of groundwater and peat oxidation.

In 1987, the Danish Parliament made the decision to restore the lower part of Skjern River and its valley. The project goal was to restore the nutrient retention capacity of the river basin, restore wetland biodiversity, and increase the recreational and tourist values of the area. This was to be accomplished by returning the river to its former meandering course wherever possible, and removing the dikes along the river so nearby meadows could be flooded. Dikes would be built where necessary to protect farmland outside the project area from flooding. The restoration project costed 234 million DKK (about $40 million). Straightening the river 30 years earlier costed 30 million DKK (approximately $4 million).

River channel construction began in June 1999 and was largely completely by December 2002. Currently, the project has re-established approximately 2200 ha of wet meadow and lakes along the lower Skjern River, increased wildlife populations in the river and Skjern delta, and reduced pollutant loading into the Fjord. Biodiversity has improved throughout the restoration area. Waterfowl populations have increased, including the return and breeding of threatened bird species such as the Spoonbill and Bittern. Atlantic salmon populations have rebounded; however, artificial propagation will likely be needed for a number of years. Otter numbers dropped after draining of the delta and this species was at risk of disappearing altogether. The restored river channel and delta improved the conditions for the otter and will likely cause numbers to increase. This improvement in ecological integrity has been attributed to a more natural river–floodplain interaction created by the reinstallation of meanders in the channel and the removal of dikes.

Summary

Ecological stream restoration focuses on the recovery of ecosystem organisms and processes with the goal of a more native, predisturbance ecosystem. Restoration plans must incorporate goals and strategies that are guided by ecological benefits and incorporate pre- and postrestoration monitoring to determine progress toward the goals. The ecological engineering approach to restoration uses environmental engineering practices in combination with ecological principles to create a starting point for biotic succession that will lead to a self-organizing and self-sustaining stream ecosystem. In this sense, human-engineered mechanical tools and evolution-engineered biotic tools (i.e., individual species) are used in concert. The biotic component of this ecosystem reacts both directly and indirectly to the surrounding environment. Some of these interactions are predictable, and these known relationships are used to base ecological stream restoration plans. Ecological stream restoration must consider the physical, chemical, and biological components of the stream, and how interactions among these components change with alterations of the environment.

See also: Erosion; Lake Restoration Methods; Landscape Planning; Material and Metal Ecology; Nitrogen Cycle; River Models; Rivers and Streams: Physical Setting and Adapted Biota; Stream Management; Water Cycle.

Further Reading

Benke AC and Cushing CE (eds.) (2005) *Rivers of North America*. Amsterdam: Elsevier.

Boon PJ, Davis BR, and Petts GE (eds.) (2000) *Global Perspectives on River Conservation: Science, Policy, and Practice*. Chinchester: Wiley.

Dodds WK (2004) *Freshwater Ecosystems: Concepts and Environmental Applications*. San Diego: Academic Press.

Drinan JE and Spellman FR (2001) *Stream Ecology and Self-Purification: An Introduction*, 2nd edn. Landcaster, PA: Technomic.

Hauer FR and Lamberti GA (eds.) (1996) *Methods in Stream Ecology*. San Diego: Academic Press.

Junk WJ, Bayley PB, and Sparks RE (1989) The flood pulse concept in river flood-plain systems. In: Dodge PP (ed.) *Proceedings of the International Large River Symposium, Special Publication. Canadian Journal of Fisheries and Aquatic Sciences* 106: 11–127.

Kangas PC (2004) *Ecological Engineering: Principals and Practice*. Boca Raton, FL: Lewis.

Leopold LB (1994) *A View of the River*. Cambridge: Harvard University Press.

Mitsch WJ and Jorgensen SE (eds.) (2004) *Ecological Engineering and Ecosystem Restoration*. Hoboken, NJ: Wiley.

Palmer MA, Bernhardt ES, Allan JD, *et al.* (2005) Standards for ecologically successful river restoration. *Journal of Applied Ecology* 42: 208–217.

Schulze PC (ed.) (1996) *Engineering with Ecological Constraints*. Washington, DC: National Academy Press.

Vannote RL, Minshall GW, Cummins KW, Sedell JR, and Cushing CE (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 130–137.

Ward AD and Trimbal SW (2004) *Environmental Hydrology*, 2nd edn. Boca Raton, FL: Lewis.

Wetzel RG (2001) Limnology: Lake and River Ecosystems, 3rd edn. San Diego: Academic Press.

Wissmar RC and Bissan RA (eds.) (2003) *Strategies for Restoring Ecosystems*. Bethesda, MD: American Fisheries Society.

Structural Dynamic Models

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Introduction
Mass Balance Models in Ecosystems
Feedbacks in Ecosystem
Actual Approaches to Model the Structural Dynamics
Applications of Structural Dynamic Models
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Introduction

The ecosystem is a well-established natural network system that consists of various kinds of organisms and abiotic components. The network is constructed on the basis of solar energy. Solar energy is converted into various materials by plants by utilizing inorganic materials, and the materials produced flow into the grazing and predation network. As a result, the energy is stocked in the ecosystems as various organisms and abiotic components.

The structure of an ecosystem changes continuously for the purpose of utilizing and stocking the solar energy with high efficiency in a given environment, which also dynamically changes. This aspect of changing is very important to understand an ecosystem characteristic; that is why mathematical models which describe the structural dynamics in the ecosystem network are required.

To understand the ecosystem network roughly, the well-known concept called 'food chain' is often quoted. In the food chain, components included in an ecosystem are divided into some trophic levels (i.e., primary producers (plants), primary consumers (herbivorous organisms), secondary consumers (carnivorous organisms), higher-degree consumers and decomposers. For example, in the water ecosystem, the food chain is assumed to be constructed by phytoplankton, zooplankton, planktivorous fish, piscivorous fish, and bacteria. In the food chain, the phytoplankton produces various organic materials by photosynthesis, and is grazed upon by zooplankton. Zooplankton is predated upon by planktivorous fish. Planktivorous fish is predated upon by piscivorous fish. The detritus produced from organisms is decomposed by bacteria in order to produce inorganic substances. This way of thinking is simple and very clear, and useful to understand the ecosystem state roughly. That is why food-chain structure is described by many ecological models.

On the other hand, many kinds of organisms are included in each trophic level in practice. For example, in water ecosystem, the above-mentioned phytoplankton includes green algae, diatoms, blue-green algae, etc. Zooplankton includes cladocerans, rotifers, copepods, etc. Furthermore, these can be divided into various species and growth stages. The predator–prey relationships among them are thus very complex, making the material flow network very intricate. This network is called as ecological 'food web'. This ecological food-web structure is also described by many ecological models.

As mentioned above, ecosystems are constantly affected by various environmental factors such as nutrient loading, temperature, human activity, etc., as well as solar radiation. If these environmental factors change drastically (e.g., high levels of a nutrient starting to load into an ecosystem abruptly), they have a strong impact on an ecosystem. The ecosystem structure changes extensively, and another ecological structure must be sought consistent with the newly given environment. The structural dynamic model is a tool for predicting or assessing the dynamic changes in such an ecological structure.

In fact, structural dynamic models are among the newly developed ecological models. In the past few decades, a good number of studies have been conducted on