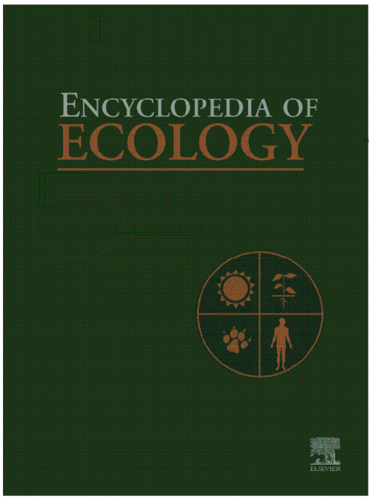

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survive and reproduce in many grassland restoration projects has been challenging. Further research is needed regarding what management techniques are important to their establishment and growth in these restored areas.

In addition to the prairie flora that is at risk, grassland animals (particularly birds and butterflies) suffer when grassland quality declines. In North America, grassland birds were historically found in vast numbers across the prairies of the western Great Plains. Today, the birds of these and other grasslands around the world have shown steeper, more consistent, and more geographically widespread declines than any other group. These losses are a direct result of the declining quantity and quality of habitat due to human activities like conversion of native prairie to agriculture, urban development, and suppression of naturally occurring fire.

See also: Agriculture Systems; Fire; Savanna; Tropical Seasonal Forest.

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Stream Management

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Introduction

Ecological stream management is the process of altering a stream ecosystem to either preserve current conditions, or change one or more components of the stream ecosystem to obtain a desired outcome. The management of larger streams and rivers differs from that of smaller streams due to the physical and ecological properties associated with an increase in scale (**Table 1**). Humans have been altering streams since at least 6000 BC when Mesopotamians began agricultural irrigation. Since then, actions such as waste disposal, channel modification, flow alterations, removal of riparian vegetation, and species introductions have degraded many stream ecosystems worldwide to a point that has significantly affected stream ecosystem integrity. Structural and functional modifications include the alteration of energy flow and nutrient cycling efficiency (ecosystem function), the reduction of native species abundances and increased species introductions (ecosystem structure), and the degradation of water quality and quantity. Many streams are presently in need of intervention to maintain or restore their ecological integrity. Several

Table 1 Relative physical differences between large rivers and small streams that affect ecosystem structure and function

	Large rivers	*Small streams*
Catchment area	High	Low
Average discharge	High	Low
Flood frequency	Low	High
Channel dimensions	High	Low
Water contact with bottom	Low	High
Slope	Low	High
Dilution potential	High	Low
Substrata heterogeneity	Low (fine)	High (coarse)
Temperature stability	High	Low
Light availability	Low (turbidity)	Low (canopy cover)/high (open channel)

approaches (such as conservation, preservation, adaptive management, and environmental engineering) have been used to accomplish this task. A newer approach to ecological stream management, ecological engineering, is a strategy that relies on both engineering and ecological theory to reach management goals.

Ecological Engineering and Streams

First introduced by H. T. Odum in 1957 as 'community' engineering, ecological engineering has the goal of attaining sustainable ecosystems that integrate human society with the natural environment for the benefit of both. One of the key aspects that separates this approach from conventional environmental engineering is a strong emphasis on ecosystem self-design and self-organization. In other words, the designer makes available the necessary components and conditions, and then natural processes arrange the components to create the most functional and efficient ecosystem. Another defining characteristic of ecological engineering is that it has both empirical and theoretical bases. The approach not only uses data collected on the cause and effect relationships through many decades of ecological and mechanical research, but also incorporates predicted outcomes of ecological reactions to environmental changes based on simulation modeling and extrapolated theories. Since it is a form of engineering, there is an explicit preplanned purpose for the 'constructed' ecosystem. In the case of stream management, the purpose is to achieve a physical, chemical, and biological state that is in accordance with predisposed human goals, but is self-sustainable. Specific intended outcomes are determined by the goals of the managing entity, and are often devised to increase aspects such as sustained resources, economic worth, or the intrinsic value of the system. Specifically, the focus of ecological engineering is to create the most natural system possible, given the current stream conditions.

Ecological engineering is well suited to ecological stream management because the self-organization process it uses fills the voids in our current knowledge of stream ecosystems. Ecological engineering uses nature to engineer aspects of the ecosystem that humans cannot. Furthermore, it can be very cost-effective to rely upon natural processes that require little monetary input as opposed to those that require continuous or repeated human intervention. For example, the self-purification (natural reduction of a pollutant as it travels downstream) characteristic of lotic systems, which is often a management emphasis, is essentially a longitudinal self-organization process whereby the system adjusts itself in changing conditions to maximize energy flow and ecosystem stability. For example, using an artificial wetland to purify waste before it enters the stream may be much more effective than chemical treatment in an industrial setting. Thus, the manager's goal is to create conditions that will maximize a stream's ability to cleanse itself naturally, and perform a defined task efficiently, such as reducing water nutrient concentrations, supporting traditional native and/or sport fisheries, or generating power.

The tools available to the manager are based in both ecology and engineering. In addition to conventional engineering stream management practices, biotic organisms are essentially tools designed by evolution, which can be used to create a network of energy flow that human engineering cannot replicate. In this sense, native species diversity can be the key to successful management because it may allow for the most efficient organizational endpoint with the highest degree of ecosystem stability. Ecological stream management through ecological engineering therefore minimizes maintenance of the system, while preserving natural ecosystems.

Ecological Stream Management

Before any management project can be implemented, identification of appropriate and feasible goals for a particular stream system must occur. A thorough attempt should be made to understand the ecology of the system, determine the threats to ecosystem integrity, and establish realistic endpoints. For ecological engineering, this

Table 2 Typical anthropogenic threats to streams

Urban	*Agricultural*	*Industrial*
Nutrients	Nutrients	Metals
Channelization	Sediments	Acids
Organic chemicals	Water withdrawal	Temperature
Pesticides	Pesticides	
Sediments	Salinity	
Pharmaceuticals	Antibiotics	

means determining current and past anthropogenic activities affecting the system (**Table 2**), understanding how the ecosystem is currently structured, and predicting how habitat and biotic modifications will most likely affect stream ecology. Although there are many other social, economic, and political aspects that are important to consider when designing a successful management program, this article focuses only on the ecological component of stream management.

Stream management is a very broad expression and encompasses many commonly used terms such as stream restoration and rehabilitation. Management is any action to intentionally change a stream's physical, chemical, and/or biological characteristics, regardless of the desired outcome. Restoration has a specific goal, which is to return a stream's ecosystem, both form and function, back to a state that is more reflective of its predisturbance condition. Since restoration is very difficult to accomplish due to permanent watershed disturbance, channel alterations, or political issues that make it impossible to recreate the predisturbance environment, this effort is more commonly referred to as rehabilitation, or restoring the ecosystem as much as is practical.

Goals and Strategies

The ecological goals of stream management can be very diverse and depend on aspects such as regional climate, permanent watershed alterations, current physical and biological state of the stream, and desired biological endpoints. Management can be geared toward getting the most natural system as in restoration, or emphasize certain components or functions of a system. For example, streams have been managed for optimum fisheries, nutrient retention, boat traffic, recreation, flood control, waste transport, or water withdrawal. Managers must often contend with multiple goals, such as restoring native warmwater fish populations while maintaining introduced coldwater sport fisheries below hypolimnetic release dams. Trying to reach a compromise between goals may lead to a compromise in ecological integrity, as optimum environmental conditions for each often cannot realistically be met.

Once specific goals have been established, the next step is to begin designing a management plan and creating strategies to achieve it. In every approach, and especially in ecological engineering, this phase is critical. Unlike typical engineering, a large part of the ecological engineering process is self-designed by nature. Once the initial conditions are set up, the system is basically left to organize itself with minimal human interference. Unfortunately, predicting exactly how the system will do this can be difficult. Using basic ecological principles, managers can get an idea of the general conditions needed to support the desired ecosystem, allowing them to determine an adequate starting point for their goal. Valuable information also can be gained from a failed management process, but associated costs may be high.

During the developmental process, project timelines should be considered. The time available for management, time in which the desired outcome is detectable, and time devoted to long-term monitoring need to be addressed. These are key questions because currently it is impossible to determine how long the self-organization process of different components will take. Given the dynamic nature of streams, a stable ecosystem may never occur to assess the effectiveness of the management project.

Another important element in stream management is the spatial scale of the project. Does the management area encompass a reach, several reaches, a segment, a watershed? Will it include riparian areas, adjacent floodplains and wetlands, the watershed, or the entire basin? These aspects greatly influence the ecological strategy and potential success of the project design, as larger projects often require much more planning and cost.

Ecological Challenges

Managers are faced with many ecological challenges that are unique to lotic ecosystems. Stream ecosystems 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. In addition, streams can vary substantially in size. Stream size and order can alter the functional importance of ecosystem components. For example, carbon sources in smaller, clear streams may be dominated by autotrophic primary producers such as algae and macrophytes, while larger, more turbid stream carbon sources are likely dominated by dissolved and particulate organic material carried down from upstream.

The longitudinal characteristics of streams also present many obstacles for successful stream management. Streams can flow through different geographic boundaries that include various forms of landscape development and pollution sources. Identifying and reducing a large proportion of these sources can often be logistically impossible. When focusing on long segments, managers must also commonly deal with tributaries and significant groundwater input. Streams regularly cross political boundaries, also making management difficult.

The Stream Ecosystem

Ecology is the study of interactions between living organism and their environment. In every ecosystem, species composition and abundance at every level, from primary producers to top consumers to decomposers, are regulated by environmental conditions. Compared to most aquatic ecosystems, stream environments are more dynamic and are characterized by nonequilibrium conditions. However, compared to small streams, larger streams and rivers are typically more stable in regard to discharge, chemical composition, and community structure. Fundamental ecological interactions among components are very important because knowing how ecosystems are likely to respond to each management action is critical to the success of a management program.

Ecological stream management focuses on the physical, chemical, and biological constraints on developing stream communities that are predictable, and uses these relationships as a starting point to design a management strategy. There are, however, many uncontrollable variables that may alter interactions, including stream size, precipitation intensity and frequency, and ambient temperature.

Following is a list of the major physical, chemical, and biological components of stream ecosystems. Included with each factor are anthropogenic actions that alter the components, and some basic, direct consequences of their alterations on stream ecosystem structure and function. This is by no means a complete list of components or consequences, as many of the basic, interacting, and synergistic effects of stream ecosystem alterations are not well known or understood.

Physical Components

Hydrology

Stream hydrology, the daily and seasonal pattern of a stream's discharge, is one of the most managed components, although some features, such as extreme floods and drought, are difficult or impossible to control. Hydrology is also one of the most important components to ecological self-organization and stability. Hydrology shapes the physical habitat within a channel by creating pools, riffles, and meanders, regulating substrata size and sediment load, and establishing a relatively stable downward slope across the landscape. Natural stream discharge, which shapes biotic communities through seasonal floods and droughts, has spatial and temporal variations in channel velocity, material transport, and headwater–downstream linkages of energy flow. Alterations to the physical characteristics of the channel, or to the amount or timing of the discharge, can affect the natural variability, and in turn the biotic communities that have adapted to it.

Changes in hydrology can be caused by channelization, dams, and/or watershed alteration from urbanization, deforestation, or agricultural development. The removal of native vegetation within the watershed or in key riparian areas and the construction of impervious surfaces strongly influence seasonal and daily discharge and increase the intensity and frequency of flooding. During storm events, reduction in precipitation infiltration, vegetation interception, and evapotranspiration increases overland flow (runoff) causing water to enter the stream quicker and in a larger pulse. On the other side of the spectrum, water withdrawal and dam construction can also cause major changes in natural discharge. Surface water and groundwater extraction for irrigation, domestic, and industrial use can lead to significantly reduced channel flows or loss of channel discharge altogether. Dams cause extensive ecosystem changes due to the considerable alteration of natural daily and seasonal discharge patterns, disruption of biological river connectivity (e.g., stopping upstream movement of spawning fish), as well as reduction of natural sediment transport, which would otherwise shape instream habitat.

All stream ecosystem processes are related to discharge. Water movement transports dissolved nutrients and particulate organic matter, and removes waste from the system. It shapes the stream channel creating habitat diversity, brings in new colonists, and allows for the migration of species across the landscape.

Geomorphology

Stream geomorphology is the development and subsequent changes of a channel's physical dimensions over time. Stream channels are naturally altered by the dissipation of energy from moving water. Regional underlying geologic features are affected differently by flowing water, so a large portion of a channel's inherent stability is dependent upon its local geologic history. For example, historically, low-gradient, meandering streams such as the lower Mississippi River, USA, that flows through fine alluvial deposits, have a high natural sinuosity with relatively low channel stability over geologic time. In contrast, approximately 2000 km away, is the steeper sloped Colorado River, which drops over 3000 m in elevation from the headwaters to the delta. This river flows through uplifted erodible sedimentary deposits of sandstone, siltstone, and shale and has created a relatively stable, highly incised channel.

Channels can be grouped into four general geomorphologically based classes: straight, meandering, braided, and anastomosing. Although helpful for differentiating general stream geometry, there is little correlation between stream class and sensitivity to anthropogenic disturbances. At a local scale, stream channels can be defined by characteristics such as length, width, depth, cross-sectional area, slope, and particle size, all of which can be directly affected by channel, floodplain, and watershed development.

A stream meanders to equalize the dissipation of energy of the flowing water, and produce an even slope as it flows through a basin. Channelization and the addition of levees on many streams have occurred in the name of flood control. Channel straightening reduces the longitudinal distance, which increases the slope between two points (i.e., increases erosion potential), reduces the pool to riffle distance ratio, reduces the volume of water a section of stream can hold, and reduces stream habitat such as woody debris. Straightening of a channel increases the velocity through the channel, which can result in increased suspended sediment and bedload, and downstream flooding (**Figure 1**).

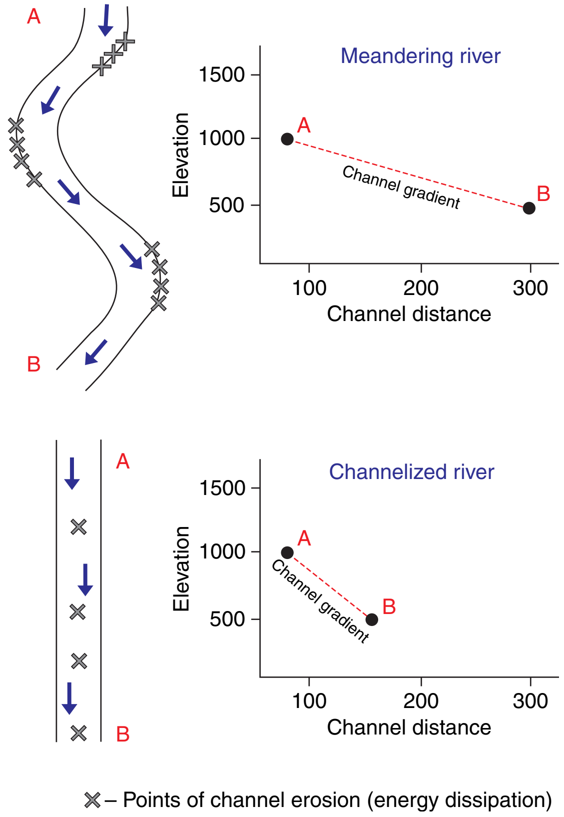

Figure 1 Example of some physical changes that occur with channelization. After channelization, the channel distance between two points is decreased, but the elevation remains the same. With the increased slope and reduction of channel bends, the potential energy of the flowing water switches from a lateral transfer of energy and sideways movement of the channel, to a downward erosional pattern and deepening of the river channel.

The biological consequences of channel modification can be significant, affecting bacteria, algae, macroinvertebrates, mussels, benthic fishes, and littoral macrophytes. Constraining the channel also reduces the interaction between the stream and its floodplain, which can be a major source of nutrient exchange. Autotrophic microbial assemblages can be altered by reductions in light availability caused by increased turbidity, and loss of shade due to riparian vegetation reduction. Reductions in allocthonous carbon from riparian vegetation, changes in substrata composition (e.g., hard and stable to soft and silty), and changes in current velocity can alter the entire benthic community.

Temperature and light

Water temperature and light affect both biological and chemical processes in aquatic systems. Although natural seasonal variation in these parameters can be great, resident aquatic organisms have evolved to deal with these regular fluctuations, by regulating metabolism, annual reproductive cycles, and changes in pigment concentration. Thermal deviations from this natural variation can occur locally due to an input of industrial or municipal wastewater, power plant effluent, increased solar input from the removal of riparian canopy shade, or reduced from input of groundwater. On both local and regional scales, hypolemnetic release dams can lower stream water temperature drastically by releasing colder water from the bottom of a reservoir, or increase it by releasing warmer water from the epilimnion.

Increased water temperature can increase the rate of metabolic activity within a system, leading to faster microbial nutrient cycling, and altered reproductive success and juvenile development of aquatic plants, macroinvertebrates, mussels, and fish. Light availability in streams can be lowered by excessive sediment loads caused by dredging, watershed erosion from agricultural practices, deforestation, or urban development. Depending on stream size, the loss of riparian cover can also increase light availability to the channel. Light availability and primary productivity are directly linked within aquatic system.

Chemical Components

Nutrients

Inorganic nutrients, mainly forms of nitrogen and phosphorus, are some of the most widespread and biologically important substances released into and transported by streams. The large number of sources, as well as multiple reactions and transformations within both the terrestrial and aquatic environments, make these additions very difficult to control and predict. Major sources of nitrogen and phosphorus into stream ecosystems can enter through both point and nonpoint sources. Point source loadings come from a discrete source such as municipal and industrial wastewater effluent outfalls, and are more easily incorporated in a management strategy since the general location of the source is known. Nonpoint sources are much more difficult to identify and address, and include fertilizer in runoff from cropland, urban lawns, golf courses, waste from animal operations, atmospheric deposition, precipitation, soil erosion, and contaminated groundwater inflow.

Most nitrogen pollution enters as dissolved nitrogen in the forms of nitrate (NO_3), and ammonium (NH_4^+), but nitrite (NO_2^-) and dissolved ammonia gas (NH_3) can be present in areas with high nutrient pollution. Nutrients can also enter streams in particulate or dissolved organic forms. NH_3 and NO_2^- in high concentrations can be toxic to aquatic life. High levels of dissolved NO_2^- and NH_3 are rarer because NO_2^- is quickly transformed into NO_3^- through microbial nitrification, and NH_3 is quickly transformed into NH_4^+ in neutral to acidic waters. The proportion of NH_3 to NH_4^+ is regulated by water pH and temperature with a shift toward NH_3 at higher temperature and pH. Once in the stream, further nitrogen transformations occur through processes such as biotic assimilation of NH_4^+ and NO_3^-, nitrification (NH_4^+ to NO_3^-), and denitrification (NO_3^- to N_2 gas). Phosphate (PO_4^-) pollution tends to enter adsorbed to sediments; however, high levels of soluble phosphorus readily available for biotic uptake are common with secondary treated municipal wastewater and runoff from large animal operations.

The most common effect of nutrient addition is an increase in primary (photoautotrophic) production. N, P, or both can limit algae and macrophyte production in streams. Thus, the limiting nutrient for each system should be evaluated, and both N and P should be considered when developing nutrient goals. Increased primary production can have positive and negative effects on the ecosystem. Expansion of the aquatic foodweb base provides a larger energy supply for consumers, which can support a greater biomass at higher trophic levels. Negative effects include a shift in algal species composition and edibility, for example, a dominance of long filamentous *Cladophora*, or toxin-producing cyanobacteria such as *Microcystis*. In streams with low discharge or in areas with minimal physical aeration, reduced dissolved oxygen levels can occur due to increased nighttime respiration and algal decomposition.

Metals

Metals such as mercury, lead, copper, cadmium, zinc, selenium, and arsenic can be introduced into streams through industrial wastewater discharges, runoff from urban and industrial areas, mining wastes, and landfills. In addition, metals can be transported long distances into remote sections of streams by atmospheric deposition in rain, snow, or dust. Metals can undergo chemical alterations to form more harmful substances once they enter aquatic systems. For example, inorganic mercury, which has a strong affinity for sediments, can be changed to organic methylmercury (CH_3Hg) by sulfate-reducing bacteria in anoxic sediments. This toxic form of mercury is lipophilic and is the major form of mercury that bioaccumulates in the tissues of aquatic organisms. Biomagnification, the increase in concentration with increasing trophic status, results in top predators becoming highly enriched in mercury.

Metals on aquatic systems tend to accumulate on benthic organic sediments, where they can persist for long periods of time even though water column concentrations are relatively low due to continuous flushing. Fluctuations in the release of metals from the sediment are quite variable and depend on the physical characteristics of sediments (e.g., texture and composition), environmental conditions (e.g., redox state and microbial composition), and individual metal properties.

Metal accumulation in aquatic organisms can have both acute and chronic effects, and negatively affect all components to the ecosystem. For example, copper levels near $2\,\mathrm{mg\,l^{-1}}$ can greatly reduce algal productivity, and the bioaccumulation of mercury, cadmium, and zinc causes reproductive and juvenile developmental problems in macroinvertebrates, mussels, and fish. Metal toxicity can also change with different environmental conditions such as temperature and pH. Much is still unknown about the effect of metals on aquatic systems, including the effect of chronic low doses and the interactive effects of multiple metals.

Acidity and salinity

A reduction in pH can occur in streams with limited buffering capacity (alkalinity). One of the main causes of anthropogenic acidity is acid precipitation. Nitric and sulfuric acids from coal and other fossil fuel combustion such as automobiles' exhaust form within clouds and are deposited onto the watershed with rain and snow. Although streams located in regions with significant industrial, urban, or mining influences are at a higher risk, acidic deposition can be transported long distances in the atmosphere and deposited in pristine watersheds that are otherwise unaffected by humans. pH-lowering acids also often enter streams through industrial wastewater discharges.

pH regulates many biogeochemical processes within a stream. For example, it regulates the proportion of NH_3 to NH_4, the solubility of potentially toxic metals such as aluminum, and microbial decomposition rates. Increased acidity can reduce the diversity of every biological component from microbes to fish, and especially harm pH-sensitive species such as invertebrates with shells composed of calcium carbonate as well as salmonid fishes.

Salinity pollution in streams can be due to the leaching of salts from soils, or caused by runoff of road salt used in cold, snowy areas. Dryland salinity occurs when a reduction of natural vegetation allows more rainfall to penetrate deeper into the soil and bring up excess salts to surface waters. Irrigation salinity occurs through the same process but the role of rainfall is replaced by irrigation water. Excess salinity in streams causes increased channel erosion due to a breakdown of the soil structure, as well as an increase in salt-tolerant species.

Pesticides and organic compounds

Herbicides, insecticides, and fungicides are frequently associated with agricultural runoff, but can also come from suburban areas and golf courses due to an increased application rate per area. The enormous variety of pesticides released into the environment (over 600 different compounds in the United States alone are in agricultural use) make this pollutant difficult to manage. Ecological effects of pesticides can be substantial and occur at all trophic levels. For example, atrazine, which is water soluble, harms photosynthetic organisms at very low concentrations ($\sim 2\ \mu g\ l^{-1}$), while dichlorodiphenyltrichloroethane (DDT), an endocrine disrupter, and chlordane, a carcinogen, can bioaccumulate in fish tissues, disrupting biochemical signals, increasing organ damage, and reducing reproductive success.

Many other organic chemicals used in industry, consumer products, and created by fossil fuel combustion also have significant detrimental effects on ecological stability. Polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) are introduced through industrial and municipal wastewater, urban runoff, groundwater intrusion, and atmospheric deposition. In addition, petroleum-based pollutants such as oil and gasoline enter through urban and road runoff, and leaking underground storage tanks. Many of these chemicals are closely associated with the sediments and can persist for many years within the ecosystem.

Endocrine disrupters have been recognized as a threat to aquatic ecosystems within the last few decades. These chemicals can mimic natural biologically active chemicals. Antibiotics and hormones, for example, estrogen and its mimics (ecoestrogens), are becoming more prevalent in stream ecosystems. Presently, the two main sources of lotic pharmaceuticals are animal feedlot runoff and municipal wastewater treatment effluent. The complete effects of pharmaceuticals on aquatic biota are not known, but have been linked to reduced fertility in reptiles, mollusks, fish, and mammals, and cause male organisms to exhibit feminine traits.

Biological Components

Species diversity

The reduction of species diversity is a common result of stream pollution. Sensitive species that cannot tolerate changing conditions are replaced by more tolerant species. This usually leads to a community with lower complexity and reduces energy flow through the system. An example of this occurred worldwide before the use of secondary treatment in municipal wastewater. Below sewage outfalls, streams would commonly be void of dissolved oxygen due to the high biological and chemical oxygen demand from organic matter decomposition. With increasing distance downstream, water conditions steadily improved due to instream biotic and abiotic processes. In the areas that were anoxic or had very low dissolved oxygen immediately below the outfall, sewage fungus, cyanobacteria, and tolerant invertebrates (such as *Tubifex*) dominate. As conditions improve, these organisms are replaced by less and less tolerant species until the algal, invertebrate, and fish community is similar to that immediately above the outfall point.

Another common change in the biotic community that accompanies human development is the alteration of native species composition. Species are often introduced purposely, such as fish stockings for sport, or accidentally through ship ballast water exchange. Changes in environmental conditions such as temperature or nutrient availability allow non-natives that are better suited to new conditions to displace native species. However, even when basic environmental conditions remain, non-natives may be better competitors for available resources and thus dominate communities once introduced. Reduction or alteration in higher trophic levels such as fish is the most noticeable, but changes in the microbial community occur more rapidly. Although most introduced species do not become established, when they do, non-native species can alter nutrient cycling and retention, change food web linkages, and possibly eliminate vulnerable native species. Ecosystem integrity is compromised when species with important functional roles are displaced without the availability of other similar species to take over the lost role (i.e., there is low functional redundancy within the system).

Ecosystem Component Interactions

Many factors listed in the last section (e.g., flow and substrata size, light and primary production, and discharge and turbidity) have a direct relationship to one another. Some of these interactions are obvious; however, many others are more complex. In addition to the unpredictability of the direct results from manipulating a given ecosystem component, interactions can vary temporally and spatially as conditions in the ecosystem change. For example, primary production in a stream may be limited by nutrients in winter when riparian shading is low, but may shift to light limitation during spring and summer. Additionally, changes in a particular component often have both positive and negative effects on other ecosystem components. The establishment of riparian vegetation reduces light and nutrients entering a stream, which can reduce primary production, but increase leaf and woody debris inputs which may increase heterotrophic microbes and macroinvertebrate shredder and collector production.

Ecological stream management is based on component interactions, and its success depends on the accuracy of predicting these interactions. A good example of the complex nature of stream management is currently taking place in the southwestern United States. The Colorado River is one of the most managed river systems in the world. Construction of the first dam (Hoover Dam) was completed in 1936, and now more than 20 dams have been constructed on the river and its tributaries. Dams were originally built to supply hydroelectric power, and irrigation and drinking water for the surrounding communities. Hydrological modifications and water withdrawals from the dams have severely altered the native river ecosystem, changing discharge intensity and frequency, water temperature, sediment movement, and native fish community structure (Figure 2). It has also unintentionally produced a productive coldwater trout fishery and endangered native fishes that depend upon warm waters and seasonal flooding. As a result, tremendous amounts of time and money have been spent managing this system to restore native fish populations, maintain a non-native trout fishery, sustain current and future power generation and water needs, attempt to reproduce natural flooding, provide recreational areas, and satisfy local Native American requirements.

Summary

The use of ecological engineering to manage streams is an emerging approach that differs from others with its reliance on self-designing ecosystems. Using ecological principles as a guide to reach stream management goals instead of conventional engineering yields a higher probability of creating more diverse, stable, and self-sustaining ecosystems. However, regardless of the approach used, successful management strategies must include realistic goals and a sufficient monitoring program to assess progress. There are still major ecological obstacles to overcome to achieve consistently successful programs. Due to logistic and financial constraints, ecosystem processes are studied much less on large rivers than on small streams; thus, information on larger lotic ecosystems often is extrapolated from research on smaller streams. Much remains to be discovered concerning the ecology of stream ecosystems, and understanding the basic physical, chemical, and biological components of streams, and their interactions, is critical. Finally, because stream ecosystems are strongly linked to their watersheds, stream management must focus not only on the stream itself, but also on the surrounding landscape, including the riparian zone, floodplain, adjacent wetlands, and, potentially, the entire watershed.

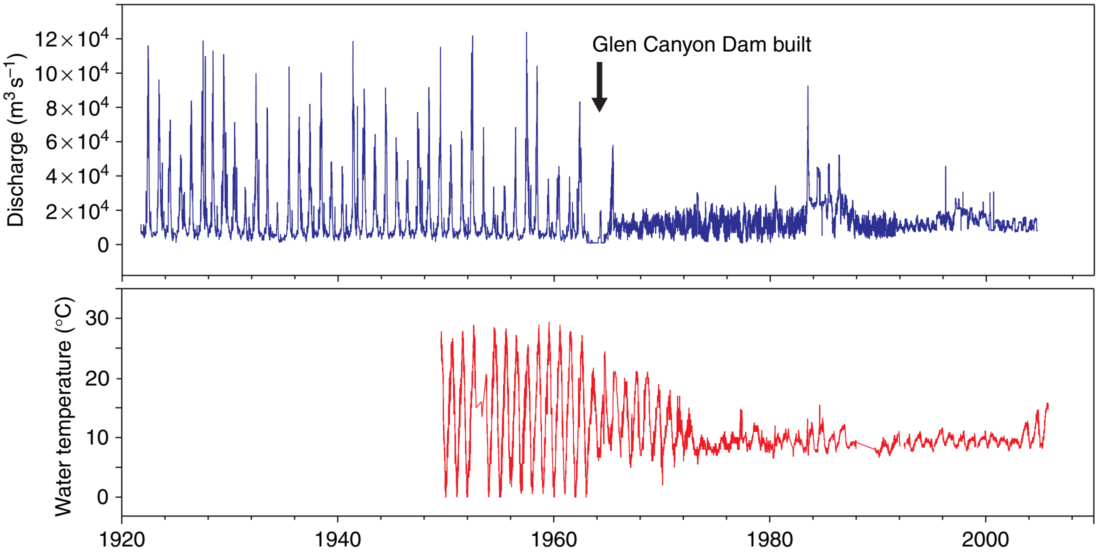

Figure 2 Example of multiple ecosystem alterations due to a single anthropogenic implementation. River discharge and water temperature for the Colorado River, USA, below the Glen Canyon Dam. Construction of the Glen Canyon Dam in 1964 reduced natural flow variability and also lowered average water temperatures due to a hypolemnetic release. Data courtesy of the United States Geological Survey.

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.

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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.