River Conservation
Challenges and Opportunities

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Chapter 11 Offprint

Ecological Restoration to Conserve and Recover River Ecosystem Services

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CHAPTER 11

Ecological Restoration to Conserve and Recover River Ecosystem Services

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Ecological restoration of rivers and streams is increasingly shifting from a focus on reference sites to a focus on the conservation and recovery of ecosystem services that benefit humans. Strategies being employed to target specific biophysical features and processes necessary to support specific services range from simple interventions to ecologically designed solutions. The success of these restoration strategies often depends on broader catchment scale factors.

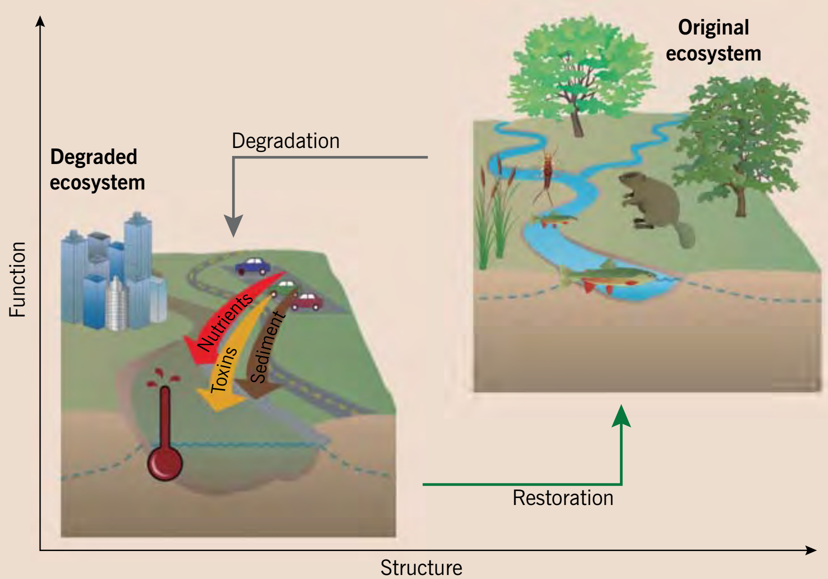
11.1. From restoring river ecosystems to restoring river ecosystem services

All living creatures depend on water for their very existence. Water is essential to basic metabolic functions, serves as a transport medium at scales from cells to biomes, and plays a critical role in global energy, mineral, and nutrient cycling. Despite this, hundreds of millions of people worldwide lack access to clean water. Most people rely on rivers for their domestic water needs as well as for irrigation, energy, and recreation. Humans also rely on the many goods freshwater ecosystems provide including flood protection offered by riparian wetlands and the source of food that fishery-rich rivers produce. However, there are many less obvious benefits that freshwater ecosystems provide such as water

Box 11.1

Ecologically successful river restoration

Figure 11.1: *All ecosystems have two major attributes – structure and function.* ***Structures*** *are attributes related to the physical state of an ecosystem and are instantaneous measures; examples include population density, species richness and evenness, standing crop biomass, temperature, etc.* ***Functions*** *are physical, biological, and chemical processes occurring within ecosystems and often are expressed as rates; examples include biogeochemical cycles, production and respiration, accumulation and loss rates, population dynamics, etc. Structure and function can be used to illustrate ecosystem degradation. Though not always the case, the original ecosystem will be characterized by both high structure and function. Degradation decreases structure and function, whereas restoration attempts to increase both attributes in the direction of the original condition*



Source: Adapted from Bradshaw (1987). Symbols courtesy of the Integration and Application Network [ian.umces.edu/symbols/], Univ. of Maryland Center for Environ. Science.

Humans have significantly modified the freshwater ecosystems on which we rely (Vitousek et al. 1997). Increasingly, river managers are turning to ecologically based restoration activities in order to improve degraded waterways. **Ecological restoration** is the attempt to return altered ecosystems to some historical condition (Box 11.1 Figure 11.1). Rivers integrate surface watersheds, ground-watersheds, and airsheds, and may arguably represent the most fundamentally altered ecosystems on Earth. In efforts to restore freshwater ecosystem goods and services, riverine and stream restoration have become both a world-wide phenomenon and a booming enterprise, with billions of dollars spent on restoration projects in the United States alone (Palmer et al. 2005). Yet, individual projects have been met with mixed success, and only recently have there been efforts to establish standards for what constitutes ecologically successful restoration.

Five criteria for ecologically successful river restoration (Palmer et al. 2005):

1. A guiding image for a healthy river must be identified *a priori*
2. The river's ecological condition must be measurably improved
3. The river must be more self-sustaining and resilient to perturbation
4. No lasting harm should be inflicted during construction
5. Pre- and post-monitoring must be conducted and data disseminated

purification, local temperature regulation, and carbon sequestration. Growing recognition that humans have and continue to seriously degrade the ecosystems upon which they depend has shifted public focus from a value- or aesthetically-based motivation to restore ecosystems to a *need*-based motivation (Palmer et al. 2004). This has had significant implications for how streams and rivers are restored, where restoration projects are implemented, and the directions restoration science has taken. We will elaborate on these, but first provide a brief overview of riverine ecosystem services and how they are linked to biophysical features within these ecosystems.

11.1.1. Restoration and ecosystem services

As river networks become increasingly human-dominated, restoration efforts will focus on the recovery of ecosystem goods and services upon which societies rely

Ecosystem goods and services are the outputs from natural systems that societies appreciate. They are benefits that people value and the reason investments are being made in river restoration. Society may be willing to pay for these outputs directly (monetary value) or their value may be quantifiable using non-monetary means (e.g. *relative valuation* where goods or services are compared and ranked). Ecosystem goods and services influence policies from regional to global levels, business transactions, and every day decisions by individuals (Figure 11.2). Ecosystem services are supported by a host of biophysical processes and ecosystem features. For example, abundant clean drinking water is an ecosystem service supported by many processes such as chemical transformations mediated by microbes and hydrologic fluxes including groundwater recharge and surface flows. This service is also supported by ecosystem features – types or components of riverine ecosystems such as vegetated riparian zones, hyporheic flowpaths, and floodplain wetlands (Chapter 9). It is important to recognize that the "products" of well-functioning and healthy rivers (in this example, clean water) are not equal to ecosystem goods and services. It is only when social value is placed on those products that they become goods and services. For instance, a healthy river that is inaccessible to people does not have social value unless individuals are willing to express a preference for preserving the existence of that river or retaining an option to use that river in the future or for future generations (Wainger and Mazzotta 2011).

Individuals rarely express preferences for the biophysical processes that underlie a riverine service (e.g. metal detoxification and organic matter decomposition may be necessary processes for the provision of clean water in some instances), thus we prefer not to adopt terminology that equates biophysical processes or ecosystem functions with services. We also think it is critical to distinguish biophysical processes and features from ecosystem services (Table 11.1) in order to emphasize the tremendous need to advance our understand-

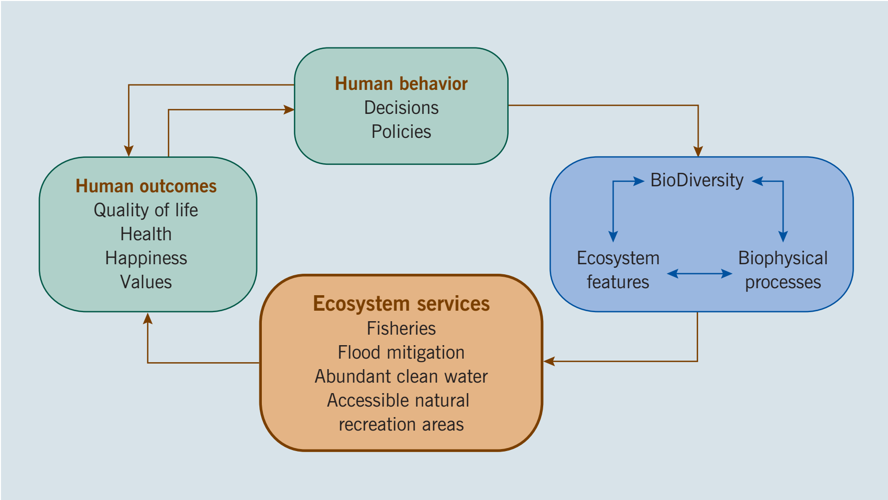


Figure 11.2: *Ecosystem services are the benefits people enjoy that come from natural systems. Their availability influences quality of life which is closely linked to human behaviors. Human behaviors, in turn, influence the components of natural systems: biodiversity, ecosystem features (e.g. different habitat types or structures at particular places), and a host of physical and ecological processes (e.g. water infiltration, nutrient cycling, primary production). Thus, the tight coupling between biophysical and social systems leads to complex dynamics for both humans and river ecosystems*

ing of when, where, and how those services are actually produced. While great progress has been made in identifying ecosystem services and developing methods for their economic or nonmarket valuation, the science behind which and what combinations of biophysical factors are essential to create and/or support these services is in its infancy.

In some instances, just a few processes may support a service, and in other cases, a multitude of complex processes interact to provide the basis for a service. For example, riverine flood control may depend almost exclusively on the presence of healthy, intact floodplains while productive riverine fisheries

Table 11.1: *Examples of riverine ecosystem services that people value and some biophysical processes and ecosystem features that contribute to the provision of those services. A few processes and structures are valued on their own and thus, depending on the context, could be considered services. Further, multiple processes and features may be linked to an individual service. This list is not intended to be comprehensive*

What people value (ecosystem services)	What makes those services possible (ecosystem processes and features)
— Clean water for drinking — Sufficient water at specific times for irrigation or hydropower generation — Flood protection — Food and food products (algae, rice, fish, invertebrates) — Recreation (fishing, swimming, water sports) — Aesthetics — Existence of species and ecosystems	— Nutrient cycling — Contaminant processing — Decomposition — Biodiversity — Water discharge and recharge — Heat and energy dissipation — Sediment transport and deposition — Riparian forests and wetlands — Floodplain connectivity — Channel form and woody debris

may depend on high rates of water infiltration in the catchment, a natural flow regime, intact riparian vegetation, and tight coupling of nutrient cycling with primary production. As such, depending on the ecosystem service a society wishes to promote, one or many processes and/or features may have to be conserved or restored.

11.2. River restoration goals

Throughout the remainder of this chapter we will discuss how restoration can work to create *potential* ecosystem services; i.e. the features and dynamic elements of a river ecosystem necessary to support a service. Riverine restoration should target those biophysical processes and ecosystem features most critical to the provision of desired ecosystem goods and services. As indicated in the prior section, the actual services assume there are social mechanisms or activities that ensure the delivery or availability of that service to people (Wainger and Boyd 2009). Quantitative relationships (i.e. equations or models) that allow us to predict potential ecosystem services as a function of biophysical processes and ecosystem features are the ecological or biophysical *production functions* underlying ecosystem service benefits.

To recover desired ecosystem goods and services, restoration actions should be guided by a scientific understanding of the mechanisms driving a river's ecological processes

For many decades, river and stream ecologists have worked to understand the factors that lead to ecological degradation and thus the need for restoration (Figure 11.3). They have also worked extensively to understand the relationships between physical processes such as discharge and sediment flux and important ecological processes and features such as rates of primary production (Young and Huryn 1996), decomposition (Webster et al. 1999), and biodiversity (Poff and Zimmerman 2010). In contrast, research on the relationship between restoration interventions and the recovery of physical and ecological processes in rivers is in its infancy. There is such a paucity of empirical data on the link between restoration outcomes and intervention practices that conservation biologists and natural resource managers largely rely on coarse-scale information based on correlations between human activities and river ecosystem degradation. For example, land use variables such as percent forest or impervious cover within a drainage basin serve as the basis for mapping the distribution of potential freshwater ecosystem services and identifying areas to be conserved or in need of restoration. Mapping services is valuable for guiding management focused on conserving parcels of land/water or on assessing the current status of services. However, mapping is typically insufficient to guide restoration actions because it does not provide ample *mechanistic understanding* (i.e. the scientific explanation behind a process) of the river and its processes.

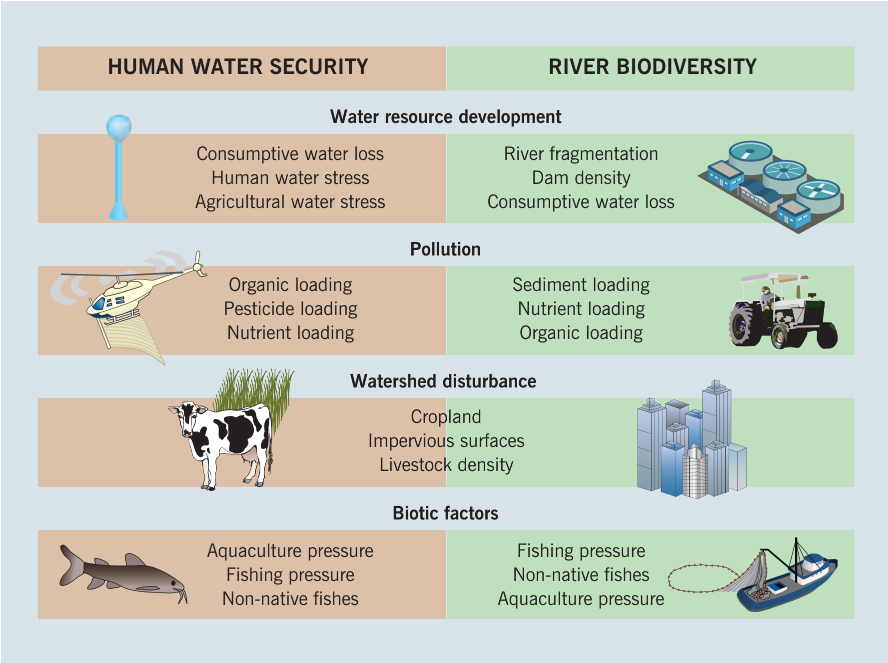


Figure 11.3: *Primary sources of river degradation that influence biodiversity* (right column) *and availability of water sufficient to ensure human well being* (left column). *Sources of increased impact are listed from top to bottom (i.e. the category "Water resource development" has the greatest impact among the four major categories, but within that category water consumptive losses have the most influence on water security, followed by human water stress and agricultural water stress)*

11.3. River restoration approaches

Selection of restoration approaches must be 1) based on a mechanistic understanding of ecological processes in rivers and 2) feasible from the perspective of managers. Correlational relationships may be adequate to predict *if* an ecological attribute is likely to exist in a particular location within a river network but not necessarily *why* or *how*. Sound restoration practices go much further because they involve hypothesizing the mechanistic links between the stressor (e.g. land use change, flow alteration, groundwater abstraction, etc.) and the state of the riverine attribute (Roni et al. 2011). These mechanisms are the key to identifying restoration interventions. For example, if we know that increased impervious surface causes increased overland flow volumes and velocities that in turn erode stream banks and incise channels, then we might target restoration efforts that reduce impervious cover within the catchment. Typically, our scientific knowledge of these mechanisms is based on data collected for systems that are being/have been degraded. But because the path to recovery may not mimic the path of degradation (i.e. *hysteresis;* Figure 11.4C), we cannot assume that quantitative relationships documented during degradation will hold post-restoration. For example, if biodiversity loss becomes significant only when certain stressor thresholds are exceeded (e.g. when impervious cover > 8-12%

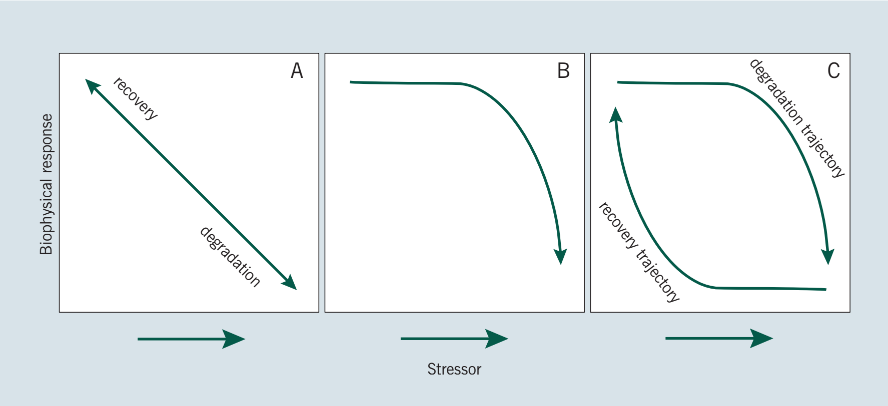


Figure 11.4: *River ecosystems respond in complex ways to stressors such as increasing levels of pollutants or uncontrolled flows due to land use change. The response may depend on the variable of interest or the context. For example, fish biodiversity may decline linearly as a stressor increases* (A – linear response), *or may remain relatively stable and only decline when a 'threshold' level of the stressor is reached* (B – threshold response). *A threshold response is particularly common when multiple stressors are acting simultaneously. Ideally, from a social and economic perspective, recovery is a direct response to restoration or management actions (as in panel A); however, many rivers exhibit a hysteresis response to disturbance such that recovery to former condition does not match the degradation trajectory and often involves a substantial lag time after the disturbance ceases* (C – hysteresis response)

[Stepenuck et al. 2002]; Figure 11.4B), does not mean biodiversity will recover if and when the stressor falls below that threshold. Hysteresis trajectories in environmental responses are quite common, and so for example, eutrophication in a river may not be reversed until nutrient levels are dramatically lower than they were at the onset of algal blooms (Duarte et al. 2009).

Correlational relationships are also often based on factors that catchment and river managers cannot influence. The "toolbox" from which managers can select when designing a restoration project may be limited by environmental policies and regulations, available funding, or social factors such as regional politics and land ownership. For example, as previously mentioned, there is a strong quantitative relationship between impervious cover and stream biodiversity, but managers are rarely able to remove all or most impervious cover in a catchment. Instead, they must focus on the fact that impervious cover limits water infiltration throughout the drainage basin which leads to a series of cascading events (e.g. rapid overland flow, bank erosion, channel incision, floodplain disconnection, groundwater table lowering, decreased base flow) that ultimately result in highly damaged waterways (Walsh et al. 2005a). Restoration efforts must focus on enhancing infiltration or some other intervention (e.g. decreasing overland flow velocities, armoring banks, re-connecting floodplains) that influences one of the other mechanistic paths that led to degradation.

As we discuss later, managers are typically tasked with implementing actions that will result in measurable benefits over small geographic scales and over short time periods. Their access to *intervention points* (i.e. where within the catchment they can implement restoration) is typically quite limited since most managers do not have policy controls that influence entire basins. In many cases, managers must understand where their tools can be effective at enhancing or restoring ecosystem services. To date, scientific research on restoration has rarely been based on starting with what tools managers and practitioners have available and where those tools can be used. Instead, most research and science-based prioritization schemes assume all options are on the table. An alternative and more realistic approach might be to ask 1) what options are possible, 2) what management/restoration tools are available, and 3) of those, which is likely to result in the greatest ecological benefits (Figure 11.5).

11.3.1. Restoration approach continuum: From conservation-based to technological approaches

Today, river restoration is practiced throughout the world and includes a diverse array of techniques that are often specific to a country or region. We can place projects into roughly four categories that vary with respect to the level of intervention (Figure 11.6). We can also characterize river restoration with respect to the broad goals that those funding or implementing projects hope to achieve (Table 11.2).

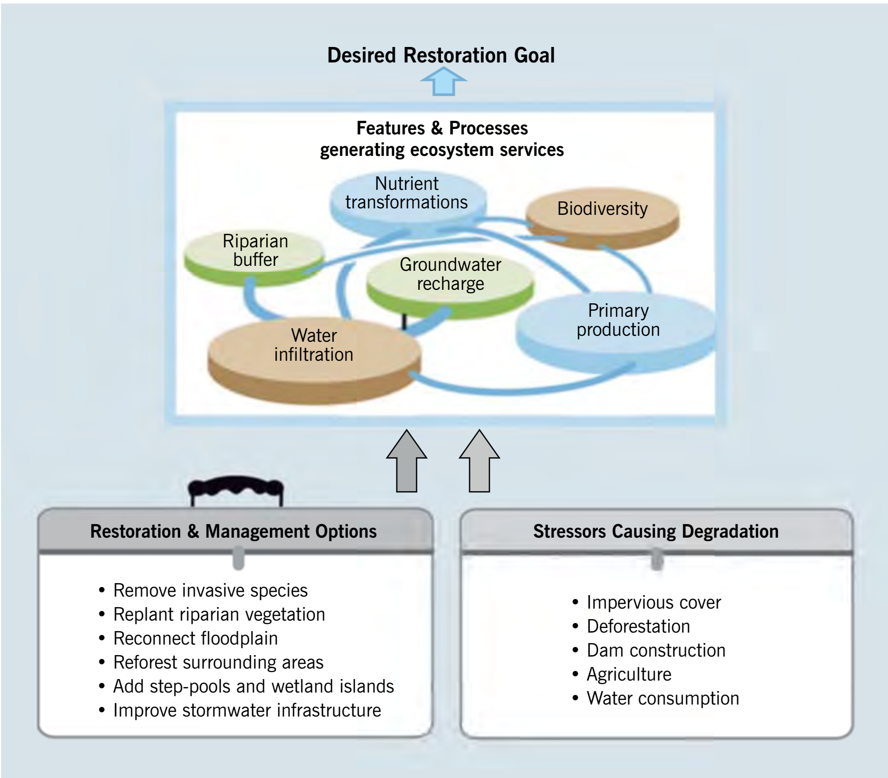


Figure 11.5: *Interventions used to restore river ecosystems must be based on the tools available to restoration practitioners and natural resource managers. Often, the stressful factors that cause river ecosystem degradation cannot be changed given the current socio-cultural context. Once the 'toolbox' of realistic options is identified, the interventions that are chosen (e.g. reconnecting floodplains or improving stormwater infrastructure) should be selected based on their ability to influence those ecosystem features or biophysical processes that are directly impacted by the degradation*

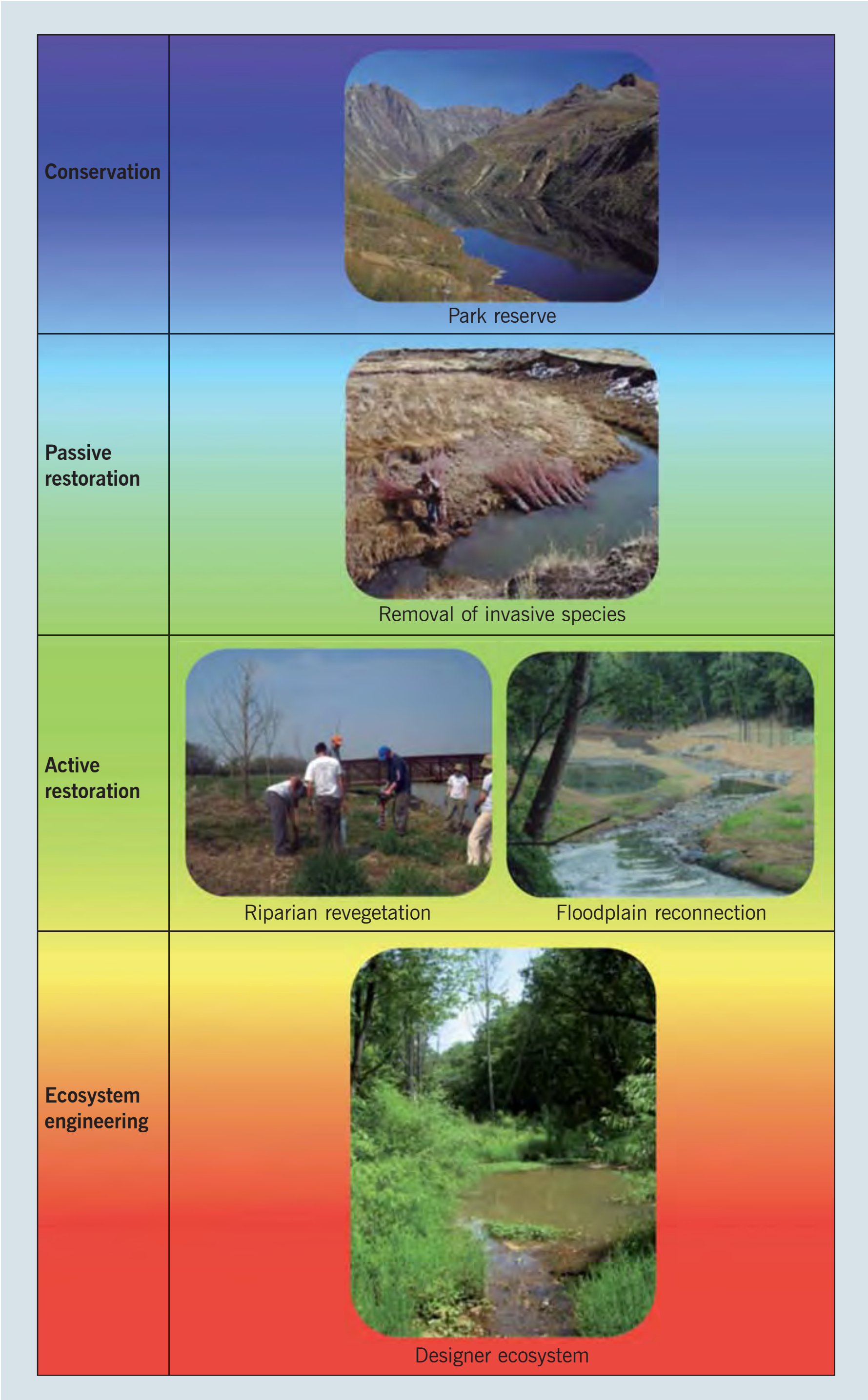


Figure 11.6: *Restoration of streams and rivers varies across a continuum from: simple* conservation *of land around a stream to protect it from expected degradation (e.g. due to encroaching urbanization) to* passive restoration *which occurs by natural processes alone after the major stressors are removed (here, invasive species were removed) to* active restoration *that involves various levels of intervention. The simplest intervention typically involves replanting vegetation along a river, but much more extensive forms of restoration are also common (e.g. bank armoring, bank grading, etc.). The end of the continuum is* ecosystem engineering, *the act of shaping ecosystems via active and passive means in order to provide desired ecosystem services. This may be accomplished by creating a 'hybrid' type ecosystem or an ecosystem type that might not be expected in a particular setting. Engineered channels are not actually restored streams and rivers since they do not conform to some past state or unimpacted reference site*

Table 11.2: *Common river restoration goals. Examples of common techniques used in river and stream restoration that may lead to ecological improvements. Most of these are part of an active restoration project. Each is based on a number of assumptions about the mechanistic link between the action and the desired goal. Qualitative 'scores' are provided to indicate the ecological effectiveness of each technique because there is generally insufficient empirical data to allow quantitative assessment of each technique's effectiveness in achieving desired goals*

Restoration goal	Specific actions	Mechanistic assumptions	Likelihood of success
Improve water quality	Planting riparian vegetation	Interception of overland flow reduces inputs of sediment and pollutants to stream	Moderate
	Soil conservation practices (e.g. no-till farming and cover cropping)	Increases water infiltration and reduces overland flow	High
	Livestock exclusion	Increases plant survival and stream bank integrity	High
	Control point source pollution	Eliminates pollutant inputs	High
	Bank stabilization	Reduces inputs of sediment from eroding banks	Moderate
	Reconfigure channels	Stabilizes stream bank, reduces erosion, enhances geomorphic complexity	Low
	Stormwater management	Reduces erosive urban flows and associated pollutants	Moderate for flow mgmt Low for water quality
Recover native species of interest or enhance biodiversity	Manually remove or kill non-native species; stock or re-plant natives	Natives will out-compete or prey on non-natives Natives will recover in the absence of non-natives	Low
	Enhance in-stream habitat (e.g. pool and riffle construction; addition of boulders or wood)	Habitat is the limiting factor, construction and structural additions will last, and desired species can colonize the river reach	Low
	Remove barriers to fish passage (e.g. fish ladder installation; culvert redesign; fish weirs on irrigation canals)	Passage is the factor limiting species recovery	High for passage Moderate for recovery
	Flow modifications (e.g. controlling the timing or magnitude of reservoir releases, limiting water extractions, adding in-stream flow diversions)	Water amount and/or timing of peak and low flows are primary factors governing species recovery	High if goal is to rewet dry streambed Low for recovery of species

Table 11.2: *(cont.)*

Restoration goal	Specific actions	Mechanistic assumptions	Likelihood of success
Recover basic river functionality	Daylight streams (i.e. redirection of a stream into an above-ground channel) Remove dams	Assumes ecological recovery will occur but time to recover depends on other sources of impairment	High for migratory fisheries in otherwise healthy catchment Limited information on recovery of ecosystem functions

High – strong empirical and/or qualitative evidence that technique is effective.
Moderate – may be effective depending on drainage basin context, exact design, and level of river degradation.
Low – reports of failure to see river improvements common.

Conservation of entire regions or habitat types associated with rivers is one of the most efficacious restoration approaches. Formal or informal policies that preserve riparian corridors or the headwaters of a river network are extremely important and effective means of restoring streams and rivers (Kline and Cahoon 2010). Protected parklands are particularly useful for conserving large tracks of land, while permanent conservation easements are good options if most of the catchment is privately owned. For the latter, a legal agreement between a landowner and government entity to restrict certain activities within a given distance from the river can promote recovery of healthy riparian corridors.

The natural – and often slow – recovery of rivers once a stressor is removed is called *passive restoration*. Putting impacted regions into conservation is certainly a form of passive restoration. Additionally, passive river and stream restoration is well documented when point source pollutant discharges are prevented, livestock are fenced out of streams, and water diversions and extractions are removed and/or prevented. This type of restoration can be remarkably effective for most streams but particularly those that are not severely or broadly impacted and those that have a high resilience capacity. For instance, rivers with an intact supply of colonists and within a catchment that has only a small area impacted will respond well compared to rivers that are highly degraded and more isolated from other healthy tributaries. Riparian corridors in grassland ecoregions that have been damaged by foraging livestock have been shown to recover quickly once livestock are excluded (Roni et al. 2002), and fish diversity can increase when barriers to upstream migration are removed (Gardner et al. 2011).

Active restoration in which streams, stream corridors, or in-stream biota or physical habitat are manipulated is assumed to be necessary in many cases – either because recovery is deemed unlikely without intervention or natural recovery would take an extreme length of time. The simplest, least expensive, and least interventionist form of active restoration is *riparian management*. This could include replanting vegetation along river corridors on agricultural or otherwise deforested land or controlling invasive plant species such as salt cedar *(Tamarix)* by manual or chemical removal. *Riparian revegetation* is among the most common restoration actions and is often combined with other active restoration approaches including bank grading, bank armoring, etc. It is important to note that while an intact riparian corridor is critical to ensure stream health, it is not sufficient – other factors such as urbanization in the catchment can override water quality or other benefits of riparian cover (Imberger et al. 2011).

In addition to simple interventionist techniques, removal of large flood and river control structures has become a common means to restore river function. Channel straightening and levee construction were historically assumed to reduce the risk of flood damage to property and human life along rivers and were thus extremely common forms of active restoration (Vitousek et al. 1997). Unfortunately, artificially straightened channels and levees may actually *increase* problems related to channel erosion and flooding (Gergel et al. 2002) both of which are expected to be even more common in regions predicted to experience higher flood magnitudes under future climate regimes (IPCC 2007). Additionally, flood control structures may actively disconnect rivers from floodplains, thereby impairing both running waters and their riparia. Removal or breaching of levees, therefore, is increasingly being considered to restore river and floodplain structure and function.

Similar to levee breaching/removal, dam removal has commonly been employed in efforts to restore natural flow regimes within river networks (Hart et al. 2002). While levees generally manage flow paths, dams serve the primary purpose of retaining water and, as a result, significantly alter natural flow regimes in rivers. As surface flow is a "master variable" in all streams, hydrologic modifications resulting from damming fundamentally alter both upstream and downstream ecosystem structure and function. While the long-term ecological benefits of dam removal can be substantial (e.g. restoration of natural flow regime, channel morphology, thermal regime, faunal dispersal), there may be adverse impacts immediately following removal. For instance, fine sediment transport following dam removal may adversely impact benthic habitat and deliver contaminants downstream (Hart et al. 2002). This suggests that from an ecosystem services perspective, societies may have to ask themselves which outcomes they most value with regard to the ecosystem in question and determine which available restoration option(s) would be most likely to produce those outcomes and over what time scales.

Restoration efforts aimed at improving water quality have also focused on floodplains as areas that slow flows thereby increasing interaction time between floodplain soils, microbes, and stream water. To date, however, few reach-scale studies that directly measure water quality benefits of *river-floodplain reconnection* have been completed, and those that have been conducted suggest only modest improvements in processes such as removal of excess nutrients (Roley et al. 2012). While decreasing flow velocities and increasing water-sediment interaction should in theory promote sediment trapping, nutrient retention/transformation, and channel stability, it is possible for catchment scale degradation to overwhelm any benefits derived from reach scale floodplain reconnection efforts (see below).

Among the most common forms of active restoration is *channel reconfiguration*. This can include a variety of actions (Figure 11.7) including but not limited to re-grading incised stream banks to reduce erosion, increasing channel sinuosity to slow flows, raising the channel bed to ensure floodplain connection during storms, and adding in-stream structures such as boulders or wood to provide additional habitat for biota and increase channel stability (FISRWG 1998, RRC 2002). In urban streams, restoration projects often focus on increasing channel

Figure 11.7: *Channel reconfiguration is a broad phrase used to describe a host of restoration projects that involve a range of earth-moving activities. In extreme cases, this might involve completely reshaping the channel dimensions (e.g. width, depth, sinuosity, etc.) as in panel A) It may also involve creating a series of step pools B) that sequentially reduce the stream power and erosion in streams that have been incised due to deforestation, agriculture, or urbanization. Many channel reconfiguration projects include detailed design plans to protect stream banks from erosion C) and/or provide potential habitat for stream biota. (All sites located in Maryland, USA)*

Box 11.2

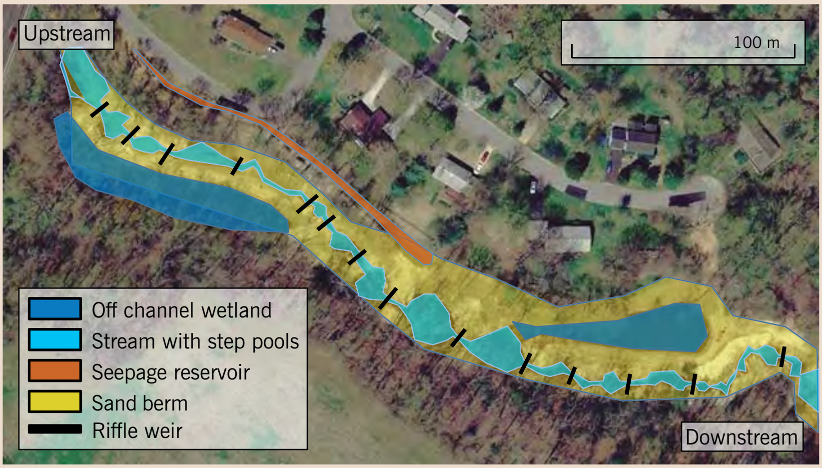
Wilelinor stream-seepage wetland: A case study in ecosystem engineering

With increasing societal demand for restoration of freshwater ecosystem goods and services, river managers and restoration practitioners are turning toward ecological engineering as a means of recovery. As an example, we highlight the Wilelinor stream-seepage wetland project – a "designer-ecosystem" recently implemented in a Coastal Plain tributary to Chesapeake Bay (Annapolis, Maryland, USA).

Problem: Urban development within the Wilelinor catchment has yielded significant sediment and nutrient loading to the stream and ultimately Chesapeake Bay. Additionally, stormwater velocities and peak flow volumes have increased due to nearly 40% imperviousness within the drainage basin. The Wilelinor stream was originally intended to provide recreational and aesthetic amenities to the surrounding communities. In recent decades, however, the stream and the benefits once enjoyed by local residents had become degraded as Wilelinor succumbed to the **"urban stream syndrome"** (see main text section IV). Residents voiced concerns with local government and demanded restoration of Wilelinor and other degraded waterways. In response to strong public interest in the restoration of recreational, aesthetic, and ecological resources, multiple state and county agencies collaborated to design a project with the goals of improving water quality and reducing peak flows and erosion.

Design approach: Rather than employing a traditional stream restoration approach (see Box 11.1), the agencies and practitioners incorporated multiple ecosystem design elements into the Wilelinor project (Figure 11.8). The result was a stream-seepage

Figure 11.8: *Wilelinor stream-seepage wetland site design, incorporating a combination of wetlands, step pool structures, sand berms, and weirs to slow storm velocities, promote floodplain wetland connectivity, increase hydraulic retention, reduce erosion, and improve water quality (38.967978 N, 76.544738 W; Annapolis, Maryland, USA)*



Source: Schematic adapted from Burke and Dunn (2010).

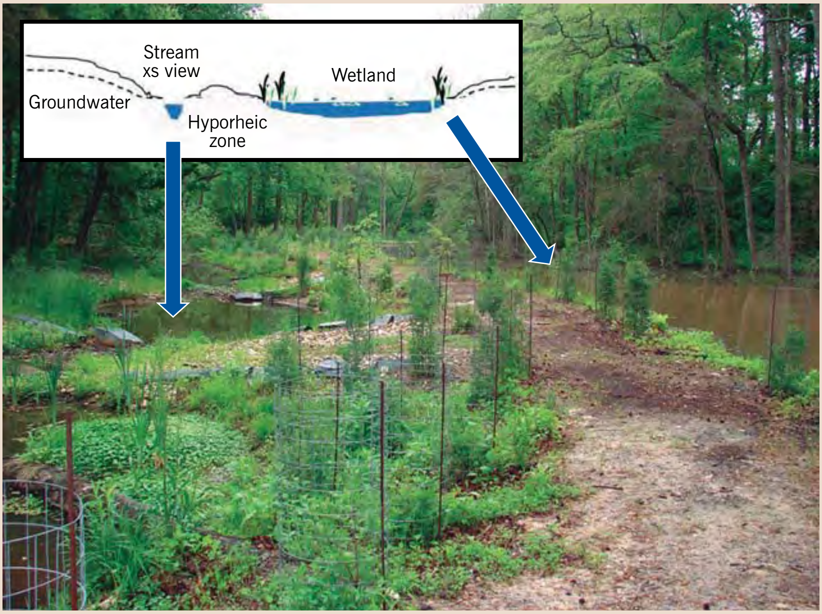


Figure 11.9:
Wilelinor is an ecologically engineered ecosystem combining both stream and wetland elements. The inset shows a cross-section schematic of the plan whereby the stream and wetland are hydrologically connected via overland flow during high discharge events and continuously via hyporheic flowpaths (i.e. below ground flow) through a porous sand berm

wetland hybrid (Figure 11.9). The design is intended to develop a stable stream profile and promote stream and floodplain wetland interaction, thereby slowing flows, reducing erosive power, and increasing hydraulic and nutrient retention.

Results: Since it was constructed in 2005, Wilelinor has been intensively monitored to assess the effectiveness of the design approach with respect to flow velocity and water quality restoration. Discharge data suggest that the stream-wetland complex effectively reduces peak flow velocity during storm events (Filoso and Palmer, unpub. data; Figure 11.10). Additionally, the system appears to be retaining nitrogen under average flow conditions and may significantly reduce N export relative to unrestored reaches (Filoso and Palmer 2011; Figure 11.11A). However, under high flow conditions, data suggest Wilelinor may not be as efficient at retaining N (Filoso and Palmer 2011; Figure 11.11B). The reduced efficiency of the system to process N under high flows is likely due to insufficient hydraulic retention and water-sediment interaction. Ongoing research is being conducted to understand the physical and biogeochemical factors governing nutrient and sediment dynamics within the stream-wetland complex. It is likely that stream-floodplain wetland interaction promoted by the project design plays a primary role in the observed reductions in peak flow and – at times – nutrient flux.

To effectively manage high nutrient and sediment loads and increase pollutant reduction capacity, streams may need to be increasingly manipulated or engineered, as

Box 11.2 *(cont.)*: Wilelinor stream-seepage wetland: A case study in ecosystem engineering

in the case of Wilelinor. It is likely that ecological engineering will play an increasingly large role in the recovery of freshwater ecosystem goods and services. Engineered ecosystems, however, may come at the expense of some portion of the fundamental structure and function of the original ecosystem (see Box 11.1).

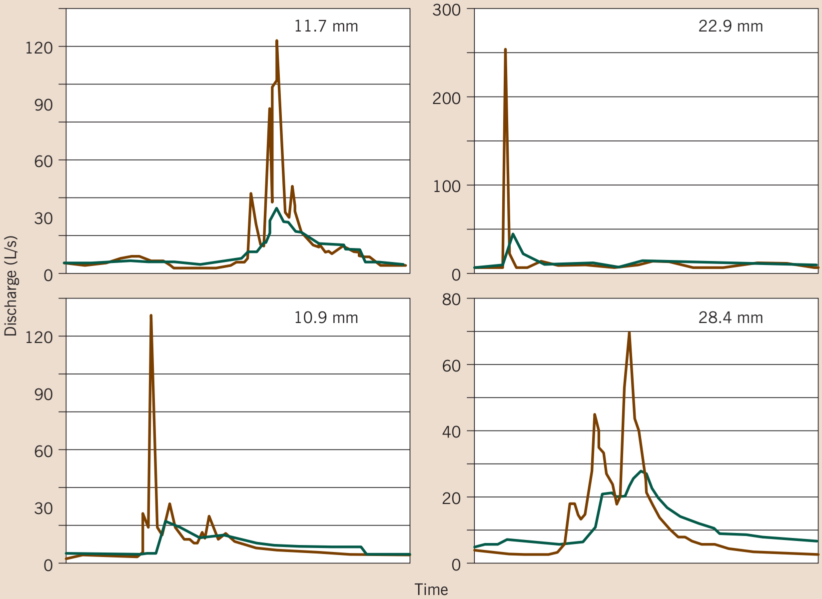


Figure 11.10: *Stream hydrographs of storm events of different sizes (rainfall in mm in each of the four insets) from discharge measured upstream* (brown) *and downstream* (green) *of the Wilelinor stream-seepage wetland system. As the four insets show, regardless of storm size, the magnitude and duration of peak stream flows were reduced*

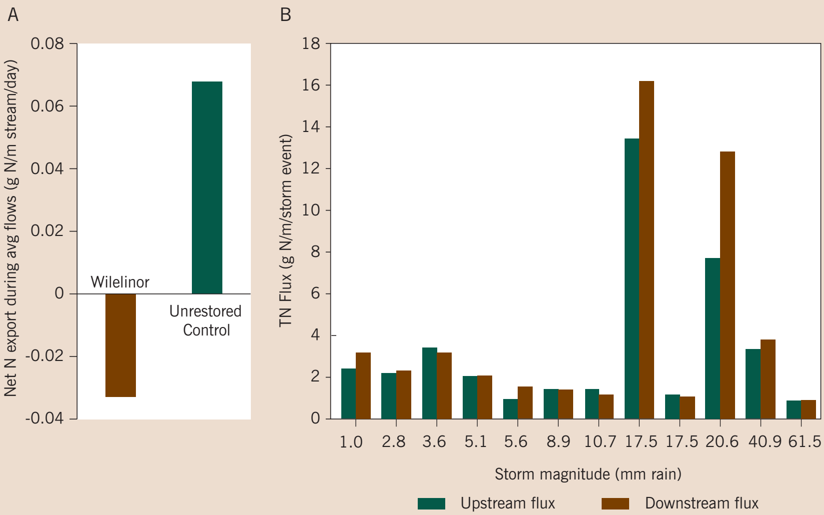


Figure 11.11: *A) Net nitrogen export during average flow conditions at the Wilelinor stream-seepage wetland and an unrestored control stream. Negative values indicate N retention. B) Total nitrogen (TN) flux upstream (green) and downstream (brown) of the Wilelinor stream-seepage wetland project during storm events of increasing magnitude*

Source: Adapted from Filoso and Palmer (2011).

stability and reducing erosive flows in hopes that in-stream biological recovery will follow (Niezgoda and Johnson 2005). Throughout the developed world, such channel-based or "hydromorphological" restoration projects are common, yet recent research efforts evaluating their effectiveness indicate that while they may stabilize banks and reduce erosion (Miller and Kochel 2010), they rarely lead to recovery of biodiversity (Palmer et al. 2010a).

Restoration in which all or part of the historic flow regime is recovered is not extremely common but represents a potential growth area as evidenced by the developing literature on *environmental flows* (Poff et al. 2010). The origins of environmental flow restoration are associated with streams and rivers in which flow diversions or extractions were sufficiently large that channels either ran dry for periods of the year in which they historically did not or water levels fell below those deemed sustainable for fish. In such instances the approach was to base flow allocations to rivers on information about the habitat needs for species of interest. Such restoration might require purchasing water rights or simply legislating minimum flow requirements. While environmental flows were originally based on minimum flow requirements, it is now widely recognized that natural variability in flow regimes is required to sustain freshwater ecosystems (Poff et al. 2010). With predicted increases in precipitation variability under future climate scenarios (IPCC 2007), environmental flow restoration is likely to be critical with respect to protecting aquatic species.

In the last decade, the concept of *ecologically engineered stream channels*, or "designer ecosystems", has sometimes led to projects that dramatically alter fluvial ecosystems – so much so that they can no longer be considered streams or rivers because they lack the geomorphic features and biodiversity characteristic of least disturbed or unimpacted reference streams in the region. Such projects typically involve a significant amount of earth-moving activity including for example, channel reconfiguration to create a wetland-stream complex which may also be connected to a stormwater reservoir of some type (e.g. Richardson et al. 2011). Step pools and in-channel sand berms may also be added to streams in efforts to enhance hydraulic retention and provide water quality benefits and habitat for wildlife. While this is often referred to as restoration, it is instead an attempt to recover specific ecosystem services using ecologically inspired approaches (Palmer and Filoso 2009). Ecological engineering is likely to play an increasingly important role in river conservation as societies shift from a focus on restoration of prototypic stream ecosystems to a focus on recovery of ecosystem services.

The concept of ecological design has been extended by some to include what is called *stream creation,* the attempt to construct a stream ecosystem where one did not previously exist. Stream creation is often confused with the common practice of *channel realignment* in which the position of a channel section or even entire reach is shifted laterally to conform to some historic condition or protect infrastructure along the channel that may be at risk due to erosion or flooding. Channel realignment is not stream creation because the river network and its longitudinal connectivity remain intact. Attempts to truly create a channel are typically proposed to mitigate for loss of stream resources due to anthropogenic activities including mining through or filling streams to extract coal or other valuable natural resources (Palmer et al. 2010b). There is no evidence that functioning streams can be created *de novo* as the few attempts thus far have failed to produce healthy streams with the full suite of ecological processes and native stream biodiversity (Palmer et al. 2010b).

11.4. Shifting restoration focus from the channel to the catchment

The vast majority of stream and river restoration projects are small in scale and isolated. Typically, individual reaches are restored, and often these are located downstream of smaller, degraded tributaries. Even when headwater tributaries are restored, if they are within a larger catchment with a high level of degradation, recovery may be minimal due to isolation from a healthy supply of plant or animal colonists. Stressors that lead to stream degradation are typically on a *catchment scale* – e.g. large amounts of impervious cover or land in agriculture. Commonly employed *reach scale* **r**estorations may be ineffective as they do not match the scale of degradation (Walsh et al. 2005b).

Despite widespread recognition that drainage basin and landscape context are critical to restoration effectiveness, only a small fraction of river restorations have been guided by a broader river or catchment management plan (Bernhardt et al. 2007). For most projects, sites are selected based on land availability. Problems stemming from opportunity-based site selection may be exacerbated if agencies and funders focus programs on specific habitat types, not broad regions (Palmer 2009). Further, regulatory frameworks may encourage small-scale, local interventions that fail to maintain the natural distribution of ecosystem goods and services. For example, under the U.S. Clean Water Act, mitigating for impacts to streams and rivers typically involves localized mitigation dictated by the amount of impact, and mitigation may result in significant spatial redistribution of freshwater resources (BenDor et al. 2009). In turn, mitigations for impacts to freshwater ecosystems may occur at significant distances from original impacts, and possibly in different drainage basins (BenDor et al. 2009). Reach scale restoration to offset impacts in a different catchment not only fails to restore structure and function within the impacted hydrological landscape, but will likely fail to yield ecosystem services equal to those lost.

When possible, restoration should be implemented at the catchment scale. Within channel reach-scale restorations are likely to be only locally and temporarily successful provided chronic drainage basin stressors are not alleviated. It is important to again recognize that managers are unlikely to have all possible restoration options and intervention points available on a catchment scale. Therefore, restoration should be approached by considering available options and tools and employing those most likely to produce the greatest ecological and/or socially valuable outcomes. For instance, managers working in urban catchments realize the importance of reducing impervious cover to alleviate the *"urban stream syndrome"* (i.e. ecological degradation of streams draining urban land and characterized by increased frequency of overland flow, increased nutrient and sediment loading, increased channel width and scour, decreased channel complexity, and decreased sensitive species [Walsh et al. 2005a]), but rarely have the power to remove all impervious cover within a catchment. However, as Walsh et al. (2005b) suggest, restoration may be used to decrease *effective impervious cover* within urban catchments (i.e. impervious surfaces directly connected to the stream by stormwater drainage infrastructure) and thereby efficiently target restoration efforts and maximize the likelihood of success.

Restoring river form may be insufficient to restore river function. A combination of conservation, restoration, and ecological design is needed to limit the loss of freshwater ecosystem services

11.5. Conclusions and recommendations

Over the course of our history, humans have modified the ecosystems on which we rely (Vitousek et al. 1997). Because river networks integrate surface watersheds, groundwater-sheds, and airsheds, they arguably represent the most fundamentally altered ecosystems on Earth. With human impacts often come the degradation of ecosystem structure and function. We are at a point at which restoring historic river form is likely insufficient to restore river function. As a result it is critical that we use a combination of conservation, restoration, and ecological design to limit further loss of freshwater ecosystem services.

We must recognize, however, that not all conservation, restoration, and design options or points of intervention will be available as we attempt to preserve the goods and services freshwater ecosystems provide. It will be increasingly necessary, therefore, to prioritize restoration efforts to maximize ecological and, in turn, societal benefits. We believe this can best be accomplished by approaching river restoration proactively at a catchment scale, rather than reactionarily using an isolated reach-by-reach approach.

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