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Key Points:

- River restoration is a prominent area of applied water-resources science
- restoration includes connectivity, physical-biotic interactions, and history
- effective restoration requires collaboration among scientists and practitioners

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The science and practice of river restoration

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Abstract River restoration is one of the most prominent areas of applied water-resources science. From an initial focus on enhancing fish habitat or river appearance, primarily through structural modification of channel form, restoration has expanded to incorporate a wide variety of management activities designed to enhance river process and form. Restoration is conducted on headwater streams, large lowland rivers, and entire river networks in urban, agricultural, and less intensively human-altered environments. We critically examine how contemporary practitioners approach river restoration and challenges for implementing restoration, which include clearly identified objectives, holistic understanding of rivers as ecosystems, and the role of restoration as a social process. We also examine challenges for scientific understanding in river restoration. These include: how physical complexity supports biogeochemical function, stream metabolism, and stream ecosystem productivity; characterizing response curves of different river components; understanding sediment dynamics; and increasing appreciation of the importance of incorporating climate change considerations and resiliency into restoration planning. Finally, we examine changes in river restoration within the past decade, such as increasing use of stream mitigation banking; development of new tools and technologies; different types of process-based restoration; growing recognition of the importance of biological-physical feedbacks in rivers; increasing expectations of water quality improvements from restoration; and more effective communication between practitioners and river scientists.

1. Introduction

Basic and applied water-resources science has matured considerably during the half century that *Water Resources Research* has been published. River restoration is one of the most prominent areas of applied water-resources science, supporting a multibillion dollar industry across many countries and helping to drive fundamental river research to address knowledge gaps that limit successful restoration. Mounting global concerns about water and environmental sustainability have driven the development and acceleration of river restoration practice and science. Drivers of river impairment, public interest in restoring rivers, and the need to ground restoration practice in scientific knowledge about river processes are all likely to continue to be important. This makes 2015 an opportune time at which to take stock of river restoration's history, contemporary status, and likely future in the context of research in water resources.

Here we first review the historical development of river restoration to provide a context for discussing the current scope of restoration efforts. We then provide critical perspectives on how the river science community conceptualizes restoration, challenges to implementing restoration designs, challenges for understanding river response to restoration efforts, and how river restoration has changed during the past decade. We conclude with a discussion of the importance of river restoration both as a fundamental testing ground for scientific understanding of rivers and as a reflection of societal attitudes toward rivers and their ability to sustain functional ecosystems.

2. What is River Restoration?

River restoration is used to describe a variety of modifications of river channels and adjacent riparian zones and floodplains, and of the water, sediment, and solute inputs to rivers [Bennett *et al.*, 2011]. These modifications share the goal of improving hydrologic, geomorphic, and/or ecological processes within a degraded watershed and replacing lost, damaged, or compromised elements of the natural system [Wohl *et al.*, 2005].

Table 1. Common River Restoration Goals^a

Goal	Description
Esthetics/recreation/education	Activities that increase community value: use, appearance, access, safety, and knowledge
Bank stabilization	Practices designed to reduce or eliminate erosion or slumping of bank material into the river channel; this category does not include stormwater management
Channel reconfiguration	Alteration of channel geometry, planform, and/or longitudinal profile and/or daylighting (converting pipes or culverts to open channels); includes meander restoration and in-channel structures that alter the thalweg
Dam removal/retrofit	Removal of dams and weirs or modifications/retrofits to existing dams to reduce negative impacts; excludes dam modifications that are simply for improving fish passage
Fish passage	Removal of barriers to upstream/downstream migration of fishes; includes the physical removal of barriers, construction of alternative pathways, and migration barriers placed at strategic locations along streams to prevent undesirable species from accessing upstream areas
Floodplain reconnection	Practices that increase the inundation frequency, magnitude, or duration of floodplain areas and/or promote fluxes of organisms and materials between channels and floodplain areas
Flow modification	Practices that alter the timing and delivery of water quantity (does not stormwater management); typically but not necessarily associated with releases from impoundments and constructed flow regulators
Instream habitat improvement	Altering structural complexity to increase habitat availability and diversity for target organisms and provision of breeding habitat and refugia from disturbance and predation
Instream species management	Practices that directly alter aquatic native species distribution and abundance through the addition (stocking) or translocation of animal and plant species and/or removal of exotic species; excludes physical manipulations of habitat/breeding territory
Land acquisition	Practices that obtain lease/title/easements for streamside land for the explicit purpose of preservation or removal of impacting agents and/or to facilitate future restoration projects

^aDefinitions from National River Restoration Science Synthesis Project.

Restoration is sometimes distinguished from rehabilitation, but we use restoration as including river management and engineering that ranges from isolated structural modifications such as bank stabilization or riparian fencing, to manipulations of ecosystem processes and biota across large river basins over a period of decades [e.g., *Warne et al.*, 2000; *Bloesch and Sieber*, 2003] (Table 1). *Bernhardt and Palmer* [2011] make a useful distinction between restoration projects designed primarily to reconnect rivers and projects designed primarily to reconfigure rivers. Reconnection efforts typically involve the removal or retrofitting of infrastructure that had previously been installed to limit the interaction between rivers and their floodplains (e.g., levees, canals) or to disconnect longitudinal flows (dams). In contrast, reconfiguration efforts aim to change the physical structure of the stream or its riparian zone through reshaping, replanting or reconstruction.

Determining what constitutes improved river conditions is highly subjective. Improvements may focus on protection of property, or esthetic or recreational enhancements that do not necessarily improve ecological functions [*Bernhardt et al.*, 2007]. Improvements may also focus on creating conditions that are not particularly natural or historically, geomorphically, or ecologically appropriate. In this sense, restoration is an unfortunate term because the word implies bringing a river system back to its former condition. Apart from uncertainty as to what point in time is being restored [*Van Diggelen et al.*, 2001; *Ward et al.*, 2001; *McDonald et al.*, 2004], or even what the former condition of a river was [*Graf*, 1996; *Wohl and Merriitts*, 2007], there are many situations in which true restoration is neither feasible nor desirable.

A more pragmatic approach is to regard river restoration as one facet of river management, but with a different goal to the river management that dominated most of the 20th century: that is, restoration can be differentiated from other forms of management in that it attempts to create or maintain some aspect of river form and function that is desirable apart from hazard reduction [*Palmer et al.*, 2005]. River restoration can thus include projects designed to improve fish habitat, water quality, or river recreation, for example. We distinguish ecological river restoration that assists the recovery of ecological integrity in a degraded watershed by reestablishing the processes necessary to support the natural ecosystem within the watershed [*Wohl et al.*, 2005; *Pander and Geist*, 2013] from restoration intended for other outcomes such as enhanced recreation.

3. Historical Development of River Restoration

People have manipulated rivers for esthetic and recreational purposes for more than a century. Esthetically driven manipulations are commonly designed to create a river form that approximates a single-thread,

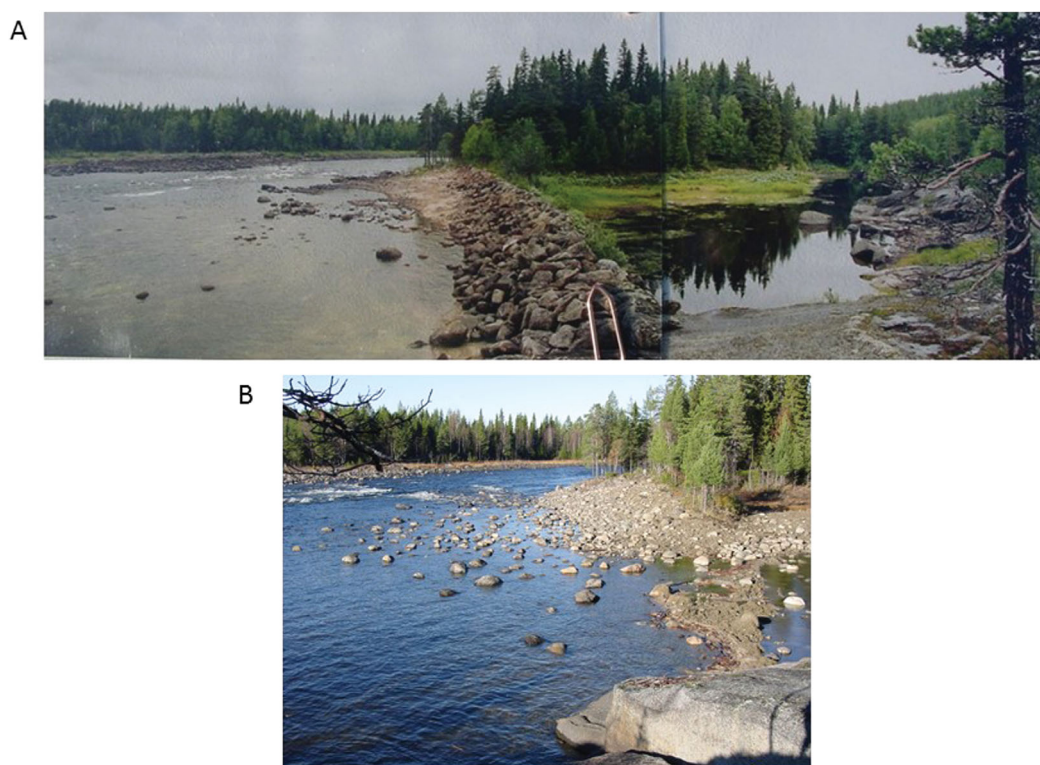


Figure 1. Example of river restoration along the Vindel River in Sweden. (a) Originally modified to disconnect overbank areas and secondary channels during floating of cut timber downstream, (b) the Vindel is now being restored through removal of bank structures such as the stone wall. Upper photograph courtesy of Christer Nilsson.

meandering channel with relatively open riparian woodland [Kondolf, 2006]. Recreationally driven river restoration dates to early 19th century instream structures designed to improve trout fishing [Van Cleef, 1885; Hubbs et al., 1932; Thompson and Stull, 2002; Thompson, 2006, 2013].

Until the end of the 20th century, however, river manipulation for esthetic and recreational purposes remained the exception to a more general approach of managing rivers concerned with enhancing navigation and reducing the risks of loss of life and property. Under this management paradigm, river corridors throughout Eurasia and North America were extensively modified [Wohl, 2014], typically with the cumulative effect of creating more uniform, physically simplified, and ecologically less diverse and functional river corridors (Figure 1) [Poff et al., 2007; Rahel, 2007; Liermann et al., 2012]. Growing recognition of how severely and extensively past river engineering has altered rivers has in turn contributed to the growth in river restoration.

Initially, restoration focused on physical manipulation of channel form, with creation of fish habitat commonly persisting as a primary objective, and accelerating during the 1980s [e.g., Gowan and Fausch, 1996]. Common approaches emphasized bioengineering using living plants [Evette et al., 2009] or dead wood [Lester and Boulton, 2008; Abbe and Brooks, 2011] and other modifications of channel morphology [Rosgen, 2011]. More recent evolution toward promoting channel-floodplain connectivity and other process-based restoration is discussed in the following section.

Form-based restoration oriented toward fish was joined in the latter half of the 20th century by a branch of river restoration focused primarily on improving water quality. The emphasis on water quality was driven initially, in the USA, by the 1972 Clean Water Act and societal concern about water pollution, and subsequently, in the European Union, by the 2000 Water Framework Directive [Bennett et al., 2011; Campana et al., 2014], as well as research indicating that management of the riparian corridor could in some cases influence nutrient flux to rivers [e.g., Burt and Haycock, 1993]. As a result of water quality requirements, restoration goals have broadened to include limiting point and nonpoint source pollution, restoring riparian corridors and floodplains to enhance retention of incoming pollutants [Prato and Hey, 2006; Craig et al.,



Figure 2. Example of restored step-pool sequence, here along the Maso di Spinele River in Italy. Photograph courtesy of Francesco Comiti.

2008], and manipulating flow and channel form to enhance uptake, storage, or transfer of diverse forms of pollutants.

4. Current Scope of River Restoration

The broad array of activities labeled as river restoration has accelerated during the past three decades, particularly in the USA [Bernhardt *et al.*, 2005, 2007], Europe [Brookes, 1990; Sear, 1994; McDonald *et al.*, 2004; Clifford, 2012], and Australia [Brierley and Fryirs, 2005]. Within the last decade, different types of process-based restoration have increased in prominence, in concert with numerous calls from researchers to prioritize river function or process in

restoration, rather than only river form [e.g., Kondolf, 1998; McDonald *et al.*, 2004; Bernhardt and Palmer, 2007, 2011]. This has included restoration that has emphasized promoting channel-floodplain connectivity [e.g., Tockner *et al.*, 1999; Shields *et al.*, 2011; Gumiero *et al.*, 2013], longitudinal connectivity and partial restoration of water and sediment fluxes [e.g., Shafroth *et al.*, 2010; Konrad *et al.*, 2011], and ecological productivity [e.g., Lepori *et al.*, 2005; Palmer *et al.*, 2010a, 2010b]. The results of these process-based restoration approaches are increasingly evaluated with respect to biotic response [e.g., Helfield *et al.*, 2007; Walther and Whiles, 2008; Lorenz *et al.*, 2009]. Simultaneously, the scope of river restoration has expanded to encompass a broader range of river types, beyond the prototypical midorder, pool-riffle meandering river. These span headwater streams in diverse settings, rivers altered by dams, large lowland rivers, and large drainage networks where restoration may involve broad, multidisciplinary efforts.

4.1. Small to Medium-Sized Rivers

Restoration efforts have moved up the drainage network, to smaller and commonly steeper streams. Artificial steps designed based on step-pool morphological criteria have been introduced as an alternative to check dams for stabilizing mountain rivers and reducing debris-flow hazards, with observed ecological benefits including organic matter retention and increased macroinvertebrate richness and diversity compared to traditional grade-control methods (Figure 2) [Comiti *et al.*, 2009]. Restoration of steep channels in urban and rural settings has adopted research insights on the hydraulics and morphology of step-pool channels into design criteria, applying geometric relationships such as the ratio of step height:length:slope from natural step-pool streams to constructed channels [e.g., Chin *et al.*, 2009]. However, coarse-grained step-pool channels, because of their ability to resist erosion and channel change during high flows, are also created in urban settings that would naturally have lower-gradient headwater streams. Palmer *et al.* [2014a] describe this form of stormwater conveyance for eroded, urban, coastal plain watersheds in the Chesapeake Bay region of the USA and note the limited ability of such streams to provide other desirable functions such as nitrogen retention or removal.

Within urban areas, stream restoration most commonly focuses on smaller streams and improving water quality and protecting infrastructure, although recreational and esthetic benefits can help to justify the costs of restoration [Kenney *et al.*, 2012]. Constraints imposed by urban infrastructure and failure to adequately consider the large hydraulic forces that can occur in narrow, rigid channels [Bain *et al.*, 2014] continue to create substantial challenges for urban stream restoration. As a result, urban river restoration may be better seen as urban river naturalization [Rhoads *et al.*, 1999]. Moreover, the reach-scale restoration common in urban areas does not effectively mitigate the watershed-scale physical, hydrological, and chemical alterations that result in loss of sensitive taxa and reductions in water quality [Bernhardt and Palmer, 2011; Doyle and Shields, 2012]. Restoring a stream can enhance public awareness and appreciation of the

river network beyond the project reach [Åberg and Tapsell, 2013; Bain et al., 2014] and thus increase community support for watershed health, but there is a significant gap between what the public considers an acceptable level of restoration and what river scientists perceive as a functional stream ecosystem [e.g., Eden et al., 2000; Cockerill and Anderson, 2014]. We consider these social dimensions in more detail below.

Restoration of mining-impacted headwater channels has included construction of water-quality treatment facilities and reconstruction of stream channels, in some cases as step-pool systems, in areas topographically altered by mining [e.g., Palmer et al., 2010a, 2010b; Byrne et al., 2012]. A synthesis of more than 400 stream mitigation projects in mining-impacted headwater streams of the southern Appalachian region of the USA, however, found that 97% of the projects resulted in suboptimal or marginal habitat even after 5 years of monitoring [Palmer and Hondula, 2014]. Sites reclaimed more than 20 years previously still contributed to significant degradation of water quality, partly because shorter lengths of perennial headwater streams were assumed to equate to longer lengths of ephemeral and intermittent streams destroyed during mining, resulting in a net loss of small streams and their functions, and partly because of an emphasis on creating channel forms that do not support lost biogeochemical and biological functions [Palmer and Hondula, 2014].

Low-gradient headwater streams in agricultural areas have been intensively altered by land drainage, channelization, grazing, and, in some regions, mill dams [Merritts et al., 2013]. Restoration of streams with numerous abandoned mill dams is problematic because of the thick sequences of millpond sediments into which channels incised after dams were breached. Bank erosion along these channels remains a substantial source of sediment and nutrients for decades after dam breaching [Merritts et al., 2013]. In many regions, historical clearing of native upland vegetation in association with agriculture created substantial aggradation in valley bottoms in the absence of mill dams [Knox, 2006; Latocha and Migoń, 2006; James and Lecce, 2013; Trimble, 2013] and these legacy sediments also continue to create sources of sediment and nutrients to streams [Hupp et al., 2013; Pizzuto, 2014]. Some restoration projects have removed legacy sediments along valley bottoms in an attempt to reconnect channels with floodplains and recreate floodplain wetlands, but details such as the presence of impermeable layers that restrict upward flow of groundwater or removal of the organic-rich horizon that retains soil moisture for plant roots can limit the effectiveness of this reconnection [Booth and Loheide, 2010, 2012]. Restoration of channelized agricultural streams can involve remeandering [Wade et al., 2002; Lorenz et al., 2009], during which a sinuous channel is artificially created and subsequently allowed to adjust to some degree, or cessation of activities such as dredging and bank stabilization that simplify or confine channels [Rhoads and Herricks, 1996]. Although remeandering and naturalization can improve ecological function of headwater agricultural streams [Lorenz et al., 2009], the level of improved function is typically limited because of continued watershed-scale stressors. For example, restoration of an agricultural stream in Indiana, USA consisting of an inset floodplain beside a channelized ditch produced only minor (< 10%) improvements in nitrate removal because of continuing high nitrate inputs from croplands in the watershed [Roley et al., 2012a].

Restoration of small to midsized agricultural rivers can also involve removal or limitation of stressors such as riparian grazing. Reduction of riparian grazing is one of the most successful and rapid means to restore diverse riparian vegetation, stream bank stability, water quality, and macroinvertebrate and fish communities [Rhodes et al., 2007; Hickford and Schiel, 2014] when other factors (e.g., flow regulation) do not limit recovery.

Water quality remains a substantial motivation for restoration of small to medium-sized rivers in urban and agricultural settings. Much of this restoration focuses on retaining water in off-channel storage areas such as the floodplain or hyporheic zone so that contaminants traveling adsorbed to fine sediment will settle from suspension and enter storage reservoirs (e.g., heavy metals in floodplains; Macklin et al., 2006) or become available for biological processing and uptake (e.g., nitrates in floodplains and hyporheic zones). In response to the U.S. Environmental Protection Agency's 2010 guidelines for total maximum daily load within the Chesapeake Bay watershed [US EPA (United States Environmental Protection Agency), 2010], for example, the Chesapeake Bay program enacted protocols that give water quality mitigation credits for stream restoration, including hyporheic restoration, reconnecting channels and floodplain, and protecting banks [Berg et al., 2014]. Most river restoration projects do not consider issues surrounding hyporheic exchange [Boulton, 2007; Gordon et al., 2013], however, despite the abundant scientific studies examining

the effects of diverse restoration strategies on hyporheic processes [Kasahara and Hill, 2006; Hester and Gooseff, 2010, 2011; Schneider et al., 2011].

Restoration can ameliorate water quality in some scenarios [Kaushal et al., 2008; Klocker et al., 2009; Roley et al., 2012a, 2012b; Lawrence et al., 2013], but tangible improvements such as reduction of nutrient inputs have proven to be difficult and elusive. In many cases water quality restoration goals have not been achieved because of lack of sufficient residence time or sufficient proportion of flow affected [Azinheira et al., 2014]. Details matter: small changes in stream characteristics such as flow velocity, bedform geometry, or hydraulic conductivity and porosity of the bed sediment can significantly alter the dynamics of hyporheic exchange and rate of contaminant removal in hyporheic zones [Grant et al., 2014; Menichino and Hester, 2014]. Reducing nutrients depends on how effectively the riparian cover buffers streams from nutrient sources [Baker et al., 2006] and the longitudinal continuity of the buffer [Weller and Baker, 2014]. Significant improvements in habitat, water quality, and benthic macroinvertebrates can lag riparian forest restoration by 10–15 years [Orzetti et al., 2010] and excess nutrient inputs can be so large that riparian zones remove less than half of the inputs [Weller and Baker, 2014]. The most effective restoration designs include features that enhance the processing and retention of different forms of nitrogen and for a wide range of flow conditions (e.g., stream-wetland complexes that buffer high flows), as well as designs that reflect important controlling factors such as position in the watershed, surface-subsurface exchanges, flow regime, and nitrogen concentrations [Filoso and Palmer, 2011].

4.2. Medium-Sized to Large Rivers

Restoration using structural and more process-based approaches has also moved down the drainage network to larger rivers. Modifications of levees via setbacks, notching, or removal have been implemented on several larger rivers in an effort to reduce flooding hazards and to restore river-floodplain habitat connectivity and associated ecosystem and geomorphic processes [Hughes and Rood, 2003; Zhang and Mitsch, 2007; Konrad et al., 2008; Marks et al., 2014; Nakamura et al., 2014]. For example, along rivers in the Central Valley of California, USA (e.g., the extensively leveed and riprapped Sacramento River), setbacks or intentional breaching of segments of old, deteriorating levees have locally restored formation of sand-splay complexes during floods [Florsheim and Mount, 2002]; improved wildlife habitat and reduced flooding risks may have also resulted [Opperman et al., 2010]. Reconnection of off-channel habitat along the Chilliwack River in British Columbia, Canada created new habitat used by a third of the wild coho salmon (*Oncorhynchus kisutch*) smolts within a few years of project completion [Ogston et al., 2015]. The Kissimmee River in Florida, USA is a well-documented example of successful reconnection restoration. Channelized by the U.S. Army Corps of Engineers between 1962 and 1971, more than 70 km of the Kissimmee were restored to a sinuous river connected to the floodplain starting in 1992. As detailed in a 2014 special issue of *Restoration Ecology*, restoration has resulted in ecologically significant changes in numerous ecosystem components, including water quality [Colangelo, 2014], benthic habitat and macroinvertebrates [Koebel et al., 2014], food web structure and ecosystem function [Jordan and Arrington, 2014], and abundance and species richness of wading birds and waterfowl [Cheek et al., 2014]. Globally, reconnection efforts have been limited in extent, relative to the scale of anthropogenic channel confinement, but are promising examples of restoration that reduces hazards and embraces geomorphic and ecosystem process knowledge.

Restoration on larger, dammed rivers has also sought to address dam-related impacts using process-based approaches oriented toward restoring water and sediment fluxes. Flow releases from dams have been manipulated in some systems to mimic elements of natural flow regimes and achieve downstream ecosystem objectives [Galat et al., 1998; Ortlepp and Murle, 2003; Flessa et al., 2013]. Ecologically oriented high-flow releases have aimed to establish floodplain connectivity and otherwise benefit aquatic organisms [Konrad et al., 2011] and, via the timing and recession rates of dam releases, to promote vegetation reestablishment such as cottonwood recruitment [Rood et al., 2003; Shafroth et al., 2010]. Documented ecological effects of environmental flow releases include shifts in macroinvertebrate communities toward predom conditions [Robinson, 2012], greater mortality among nonnative *Tamarix* seedlings than among native *Populus* [Wilcox and Shafroth, 2013], and reproduction of the endangered cui-ui sucker [Rood et al., 2005]. Many environmental flow releases have focused primarily on fish [e.g., Jacobson and Galat, 2008], but in general there appears to be little direct evidence of resulting improvements in fish communities. Geomorphically based high-flow releases from dams have aimed to mitigate dam-related changes in sediment dynamics, for example in Grand Canyon where flow releases have sought to redistribute sand and rebuild bars and



Figure 3. Example of river restoration through removal of grade-control structures along the Mareit River, Italy. View on the left is from 2005, prior to restoration. View on the right is from 2010, after restoration. Photograph courtesy of the Department of Hydraulic Engineering, Autonomous Province of Bozen-Bolzano, Italy.

have been timed to take advantage of tributary sediment inputs [e.g., *Melis*, 2011; *Mueller et al.*, 2014]. Sediment deficits downstream of dams have also been addressed by gravel augmentation, including on the Rhine River, where annual coarse-sediment additions are oriented toward protecting downstream infrastructure, and elsewhere in Europe, Japan, and the US, where the focus of such efforts is most commonly on fish habitat restoration [Kondolf et al., 2014]. Bypassing sediment around dams via a range of engineering approaches represents a promising yet rarely implemented method of maintaining downstream sediment regimes [Kondolf et al., 2014].

More comprehensive restoration of dammed rivers has entailed dam removal. Both the pace of dam removal and the size of dams removed have increased, restoring fluxes of water, sediment, wood, and nutrients, as well as connectivity for aquatic organisms [e.g., *Major et al.*, 2012; *Wilcox et al.*, 2014; *East et al.*, 2015; *O'Connor et al.*, 2015]. For many types of stream restoration, benefits or achievement of objectives are difficult to evaluate. Dam removal effects (e.g., on fish passage) tend to be more immediate and visible [e.g., *Kornis et al.*, 2014], although the details of fish dispersal following dam removal depend on factors such as life history patterns of each species, proximity to source populations, and habitat diversity [Pess et al., 2014]. Removal of grade-control structures, such as on the Mareit River, Italy (Figure 3), has represents another approach to restoring longitudinal connectivity.

Structural approaches to river restoration have also been applied to larger rivers, both to mitigate ongoing dam impacts and as part of dam-removal projects. In the Kootenai River, Idaho, USA, channel modifications, including J-hooks and reconstruction of side channels, have been implemented in a reach downstream of Libby Dam in an effort to improve sturgeon productivity and spawning success. Structural approaches on the Kootenai have been complemented by broader efforts to improve floodplain and channel ecological function, awareness of flow and sediment supply, and application of tools such as morphodynamic modeling to guide restoration [McDonald et al., 2010; *Kootenai Tribe of Idaho*, 2013]. In postdam-removal scenarios where managers wish to control erosion in formerly impounded reaches, new channel construction has been used as an alternative to allowing channel formation to evolve naturally. In the Clark Fork River, Montana, USA, new channel construction in the reach formed following the removal of Milltown Dam, where

the presence of contaminated reservoir sediments constrained management, exemplifies the application of structural restoration approaches to larger rivers [Woelfle-Erskine *et al.*, 2012]. Efforts to reconstruct sections of larger rivers for restoration goals are highly experimental, and the response of such projects to large floods and/or continued sources of upstream degradation bear watching.

5. Critical Perspectives on River Restoration

Even as broader consideration of river process and restoration outside of the river corridor has taken root, the research community has emphasized two persistent themes in river restoration: the limited monitoring of restoration projects to quantitatively and objectively determine whether restoration goals were achieved [e.g., Bernhardt *et al.*, 2005] and the high proportion of restoration projects that do not achieve significant improvements in river function as reflected in criteria such as water quality or biological communities [Lepori *et al.*, 2005; Bernhardt and Palmer, 2011; Violin *et al.*, 2011; Palmer and Hondula, 2014]. We can add to these a third challenge of more effectively incorporating the nonscientific community into river restoration planning and implementation [Eden *et al.*, 2000; Pfadenhauer, 2001; Wade *et al.*, 2002; Eden and Tunstall, 2006; Eden and Bear, 2011]. The apparent widespread failure of many restoration approaches highlights the need to understand why a substantial portion of restoration projects do not achieve their objectives and how the research community can contribute to making restoration more effective. We see three core challenges that research needs to address if progress is to be made in river restoration: (1) the problem of conceptualization and how we approach restoration; (2) developing restoration projects at the interface of science and society; and (3) in relation to the science of restoration itself.

5.1. The Problem of Conceptualization: How do We Approach Restoration?

Thinking about how we conceptualize river restoration is crucial to a critical analysis of existing restoration practice. The ecological literature conceptualizes restoration as a process [e.g., Hobbs and Norton, 1996; Higgs, 1997; Hobbs and Harris, 2001]. Central to this process is identifying restoration goals, commonly based on an appropriate model of ecosystem response, as well as the recovery of biotic community composition [Hobbs and Harris, 2001; Higgs, 1997; Hobbs and Norton, 1996]. Thus, a proper conceptualization of river dynamics (physical, ecological, chemical) informs the identification of restoration goals or objectives, and in turn, should determine how we evaluate the success of the restoration process.

Under the assumption that we can map ecosystems onto physical elements of the river environment [Newson and Newson, 2000], restoration can be conceptualized as involving interventions to improve the structure or form (e.g., pool-riffle topography), function (e.g., flow acceleration and deceleration, nutrient uptake and release [e.g., Ehrenfeld, 2001; Ward *et al.*, 2001]), diversity, and dynamics of river corridors [McDonald *et al.*, 2004]. Interactions between form and process are responsible for diversity (i.e., the spatial variability in physical habitat present) and dynamics (i.e., change in river channel structure through time). Following Palmer *et al.* [2005], we should consider restoration as aiming to achieve a dynamic ecological endpoint, “the least degraded and most ecologically dynamic state possible, given the regional context” [Palmer *et al.*, 2005, 2010a, 2010b]. That is, we should be aiming to restore a dynamic state as characterized by spatial and temporal variations in biotic abundance and composition that reflect those in reference systems, and channel geometry that changes in response to natural flow variability.

Recognizing the spatial and temporal variability of river ecosystems has at least three important components. First, it counters the notion that restoration is about recovery to a particular equilibrium state, one which is too often interpreted as a stable state [Adams, 1997; Hobbs and Harris, 2001]. River ecosystems exhibit a natural or historical range of variability (HRV) in relevant parameters such as flow and sediment regimes, channel form, or biological communities [Morgan *et al.*, 1994] as a result of disturbances and other changes in external forcing [Wohl, 2011]. Rivers respond to this variability in ways that maintain their diversity. Thus, restoration must embrace the restoration of diversity and not simply restoration of a particular river structure or form.

Second, recognition of spatial and temporal variability means that we need to rethink the role of history in informing restoration projects. It counters the idea that restoration is about going back in time to identify a particular river channel structure or form that should be restored. Rather, the role of historical enquiry is to understand how the river works and how it has been impacted upon by watershed-scale changes. This

information becomes the basis for identifying the necessary conditions for ecosystem recovery, and informing potential manipulations that sustain the processes and structures needed to support particular restoration goals.

Third, recognition of spatial and temporal variability facilitates acceptance that the dynamics and diversity of rivers are important for sustainable river restoration [Ward *et al.*, 2001]. There should be variability in what we expect to see, and where, within a river basin. The diversity identified (and restored) will necessarily scale with the size of the basin being considered. Because rivers and the boundary conditions (climate, landscape, etc.) that force them are dynamic, any particular spatial variability is unlikely to remain fixed in time. In turn, this requires us to think critically about the kinds of metrics that we use to quantify rivers, and how these metrics respond to river restoration efforts. There is much to be gained from ecological science, which has been sensitive to the questions of spatial and temporal scale in the description of ecosystem properties.

Finally, considering diversity and dynamics is useful because it allows restoration to be tied to resilience and recovery, and hence the importance of considering sustainability [e.g., Eden *et al.*, 1999; Van Diggelen *et al.*, 2001; Whalen *et al.*, 2002] as a metric during restoration. Ecological theory suggests that spatial environmental heterogeneity should promote biological recovery [Holling, 1973; Gunderson, 2000], although promoting ecologically relevant forms of heterogeneity can be challenging [Lepori *et al.*, 2005].

The challenge that comes from this kind of conceptualization is its implementation. Should we restore form/structure, function, or some combination of the two? Following Palmer *et al.* [1997] and McDonald *et al.* [2004], we can distinguish three kinds of intervention: (1) “field of dreams,” where the desired consequence of restoration (e.g., a meandering river) is identified and the river is engineered using a structure-oriented approach focused on restoring the forms of the river that have been lost [Adams *et al.*, 2004]; (2) “system function,” where more emphasis is placed upon restoring desired processes in the system, and the system is allowed to develop in response to the restoration; and (3) a compromise or hybrid “keystone” approach which recognizes that crucial elements of both the structure and the function of a river may need to be restored (e.g., riffle-pool units as keystones), but where there then needs to be scope for the river to evolve in response to the introduced structure and function. Both the system function and the keystone approach have gained favor among ecologists because the field-of-dreams approach emphasizes goods and services such as recreation or water quality, rather than the processes necessary to deliver and to sustain those goods and services [Christensen, 1997].

Distinguishing these three types of intervention emphasizes how interactions between structure and function create system dynamics and diversity, and the challenges this presents for river restoration [Shields, 1996]. An irony of river restoration is that restoring particular structures to a river (e.g., river meanders) requires additional measures to manage the natural relationships between structure and function that may result. For example, river meanders naturally lead to secondary circulation that can in turn lead to bank erosion and bend migration. Restoring meanders should necessarily reintroduce these dynamics, but restoration projects may involve the installation of structures such as bank revetments or bendway weirs to counteract these processes.

All three types of intervention still require assessment of what should be restored, which involves identifying an appropriate reference condition. For example, a field-of-dreams approach seeks to identify a possible river regime (e.g., slope, channel pattern, bed material) and to reinstate the morphology associated with that regime as the reference condition to which the river must be restored. McDonald *et al.* [2004] identify three problems with such an approach: (1) the assumption that a particular regime leads to a singular or reference river condition rather than there being two or more possible conditions [cf. Graf, 1988]; (2) the difficulty of identifying such a condition historically [cf. Van Diggelen *et al.*, 2001; Ward *et al.*, 2001]; and (3) the expectation that the river will be self-maintaining in the regime envisaged. Regime analyses tend to produce statistically stable states only in the absence of external forcing. If a restored river occurs within an evolving system (e.g., such as due to a change in discharge), then the state identified may not be meaningful. Consequently, the notion of a reference condition has evolved in academic thinking to consider an HRV [Morgan *et al.*, 1994] that can provide a basis for identifying restoration options [Wohl, 2011].

Applying HRV as a means of restoring rivers needs to recognize how human activities or wider environmental change might restrict the extent to which the variability characteristic of the reference period may be

reintroduced [e.g., Palmer *et al.*, 2005; Wyzga *et al.*, 2012a]. Although the system function approach and keystone approaches are more amenable to the idea of an HRV, such approaches may be difficult to implement if the river corridor does not have the space available for the river to be dynamic, or if there are wider basin constraints such as flow regulation that cannot be restored. There is now a good body of literature that shows how it is possible to identify HRV [e.g., Downs *et al.*, 2011; Fryirs *et al.*, 2012; Julian *et al.*, 2012; Rathburn *et al.*, 2013] so as to inform restoration [e.g., Baillie *et al.*, 2011; Rubin *et al.*, 2012; Woelfle-Erskine *et al.*, 2012], but also recognizes that this variability may be evolving due to wider basin-scale changes that may not necessarily be reversible [e.g., Petterson *et al.*, 2010; Layzell *et al.*, 2012; Persico and Meyer, 2013]. There is much less research that has demonstrated how to implement an approach based upon restoring system function [Palmer *et al.*, 2014b].

The three distinct approaches to restoration also contrast different scales of intervention. The field-of-dreams approach tends to focus on river reaches, or restoration of relatively short sections of river, with objectives defined according to perceived local needs [Kondolf, 1998; Eden and Tunstall, 2006]. This may also apply to system function and keystone approaches, but their focus on process restoration implies an increase in the spatial scale of analysis. This reflects a recognition that effective restoration of individual river reaches may be limited by fundamental root causes [e.g., Kondolf, 1998; Pedrolí *et al.*, 2002], such as the impacts of altered inputs of water, sediment, nutrients, and contaminants from the entire watershed [Bernhardt and Palmer, 2011; Violin *et al.*, 2011; Doyle and Shields, 2012]. It has been argued that a more basin-scale approach is needed [e.g., Palmer *et al.*, 2005; Lane *et al.*, 2008], but such a change in scale raises new challenges. First, any increase in spatial and temporal scale will also imply an increase in the range of issues that have to be addressed in restoration [Adams *et al.*, 2004], including channel-floodplain connectivity and hyporheic exchange, for instance. Second, there may be limits to which larger scale (e.g., basin) management may be feasible because as scale increases so will the number and range of organizations responsible for and interested in restoration [Van Diggelen *et al.*, 2001]. Third, the effects of basin-scale restoration may be much harder to predict [Hughes *et al.*, 2001] and it may take time for the restoration to result in a change in river configuration. Finally, if increasing scale also implies increasing the range of issues to be considered, then the benefits that result may be more than simply an improvement in river structure or function, and other parameters such as water quality may improve [Jarvie *et al.*, 2013]. This implies a more multicriteria approach to setting and evaluating restoration goals [e.g., Pander and Geist, 2013]. We contend that it is not surprising that examples of catchment or basin-scale restoration efforts remain relatively few [e.g., Ramchunder *et al.*, 2012; Waltham *et al.*, 2014] as compared with more reach-scale initiatives.

5.2. The Critical Challenge of the Science-Society Interface

Even if it is possible to develop a clear conceptualization of river dynamics, to use this conceptualization to inform restoration goals and in turn to identify the criteria or metrics that deem restoration a success, the question arises as to who should be involved in setting objectives? In this section, we argue that river restoration must be considered in reference to its social context [e.g., Wyant *et al.*, 1995; Hobbs and Norton, 1996; Higgs, 1997; Hobbs and Harris, 2001; Pfadenhauer, 2001] because of: (1) wider democratic questions over who has standing to set an objective for the river [Eden and Tunstall, 2006]; and (2) practical questions, as implementation of restoration may depend upon the acceptance of restoration outcomes by those who live with a river and its floodplain [e.g., Tunstall *et al.*, 1999, 2000; Buijs, 2009; Åberg and Tapsell, 2013].

Ecological restoration more generally did not originate as an academic science but as a citizen-led, public project [Gross, 2002]: it was only during the 1990s that restoration ecology shifted as a result of academics' desire to ground restoration more firmly in academic science. The origins of restoration, including river restoration, can be traced back to a desire to restore a different relationship between nature and society. Thus, we can see the growth of an academic science of river restoration as an attempt to better define what this "nature" should be. But to see such definition and implementation as simply an academic issue would overlook the origins of restoration as a social movement [Gross, 2002] and the constraints and opportunities afforded to restoration through its role as a social process.

Restoration carries financial [Holl and Howarth, 2000] and other costs [Junker *et al.*, 2007]. Developing a sustained interest of local communities in river restoration [e.g., Åberg and Tapsell, 2013] is particularly important for maintaining community support for the project. Rivers are a source of both potential value (e.g., recreation) but also substantial concern (e.g., flood risk) for those who live with them [e.g., Jacobs and Buijs,

2011; Seidl and Stauffacher, 2013]. If restoration objectives are dependent upon the continued commitment of those who live with the river or who influence policy decisions, then they have to be set in terms that are socially relevant and acceptable [Tunstall *et al.*, 1999, 2000; Junker *et al.*, 2007; Buijs, 2009; Åberg and Tapsell, 2013; Yocom, 2014]. Social relevance is strongly bound to emotional and esthetic factors that govern whether communities consider a restoration project to be successful [Buijs, 2009; Jacobs and Buijs, 2011; Yocom, 2014]. Rivers may have acquired social value even if they are ecologically degraded [e.g., Adams, 1997; Junker *et al.*, 2007] and research has shown that elements that a river restoration scientist might view as necessary for a successful restoration in biophysical terms may not be the same as those that a community might value [Che *et al.*, 2014]. Further, the more natural elements of a river landscape, which may be the aim of an ecologically driven restoration, may be viewed negatively (e.g., gravel bars in braided rivers; Le Lay *et al.*, 2013].

These observations show why rivers should be seen as a hybrid of nature and culture [Eden *et al.*, 2000; McDonald *et al.*, 2004] and this has major implications for the implementation of river restoration projects. However laudable scientifically or ecologically informed goals for restoration might be, a failure to consider the interface between restoration science and society is likely to cause divergence among the goals of academics, practitioners, and those who live with rivers. Setting objectives and implementing river restoration may have to attend to the communities that sustain it financially, culturally, and politically [e.g., Mann *et al.*, 2013; Seidl and Stauffacher, 2013]. Such attention may be needed to make river restoration a more democratically accountable process and to respect the origins of restoration as a social movement. It may also be needed because of the powers that exist within communities to halt restoration projects. For instance, Swiss water law was strengthened in 2011 to require cantons to have a plan and a timetable for the naturalization of water courses. This imposes limits on the kind of river management that a canton can authorize and support financially and would seem to support river restoration. But the tradition of direct democracy in Switzerland means that a river management project can be rejected by a popular vote if enough signatures can be obtained. In this kind of system, methods for reconciling conflicting objectives for river restoration are imperative to achieving restoration. In other countries, such as England and Wales, river restoration may be part of a planning process in which a planning application is considered by trained planning officers, who make a recommendation to the democratically elected government officials, who then decide on the application in light of overarching legislation. A contentious restoration project can also be derailed through this process, even if not as easily as in Switzerland. Thus, there may be an imperative to incorporate social values into river restoration to reduce the probability that a project may be slowed or abandoned as a result of established decision-making processes [Junker *et al.*, 2007] or that the project may be altered to the detriment of achieving ecological enhancement [Åberg and Tapsell, 2013]. In short, it requires new ways of practicing river restoration that challenge old ways of managing rivers socially and politically [Eden and Tunstall, 2006].

Research has shown that people can develop enthusiasm for restoration if appropriate mechanisms for community engagement can be identified [Tunstall *et al.*, 2000]. Wider experience of public participation in river management provides some context for how such community involvement might be achieved [Lane *et al.*, 2011]. (1) In a deficit approach, the public is assumed to lack sufficient knowledge, such that education is required for them to accept the options being proposed. However, people who live with their rivers are typically experts in their own right [Collins and Evans, 2002; Eden and Bear, 2011]. Simply treating the public as deficient and needing to be educated [Sturgis and Allum, 2004] in the hope that they may make decisions more rationally [Callon, 1999] imposes the opinion of certified experts as to what is the objective of restoration. (2) In a deliberative approach, the public are consulted over management options produced by those with (certified) expertise. This recognizes that citizens may have substantial knowledge in relation to a particular question [e.g., Yearley, 2006]. An important consideration is where in a project public consultation occurs on the spectrum between “downstream,” in which engagement occurs once a project proposal has been developed and public opinion is sought, and “upstream,” in which engagement includes discussion of the objectives before a project has been designed. This latter form is more radical, but has been tried in watershed restoration [e.g., Costanza and Ruth, 1998; Johnson, 2009]. (3) Approaches based on coproduction see public involvement as occurring through a process of negotiation and renegotiation, throughout and beyond the management process (i.e., starting before objectives are set). Coproduction recognizes that deliberation on its own tends to leave intact the knowledge and desires of certified experts and

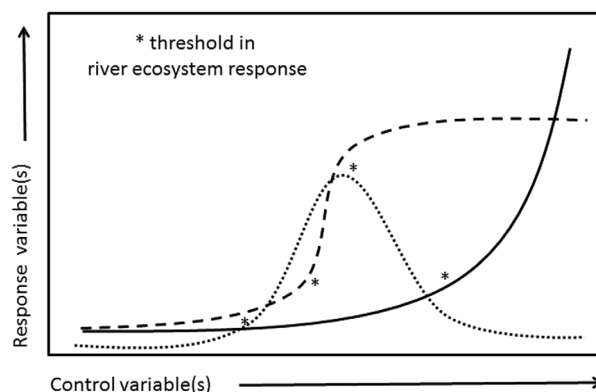


Figure 4. Illustration of two forms of hypothetical response curves. The control variable(s) would be the factor being manipulated through restoration: examples include flow regime, sediment regime, extent of riparian zone, connectivity with the floodplain, backwater habitat, connectivity with the hyporheic zone, and so forth. The response variable(s) would be the desired objective of restoration, such as nutrient retention, water temperature, macroinvertebrate biodiversity, fish biomass, and so forth. The shape of the response curve can be quite diverse between different pairings of control and response variables and different river ecosystems.

managers and those of citizens [Lane *et al.*, 2011], even if they stand in opposition [e.g., De Groot and De Groot, 2009; Jacobs and Buijs, 2011; Seidl and Stauffacher, 2013]. Thus, public engagement through deliberation tends to reinforce the power of political processes in decision-making, sometimes to the detriment of the knowledge upon which those processes are supposedly based. Coproduction recognizes that science proceeds by putting existing knowledge on trial (i.e., by hypothesis testing) [Callon, 1999], recognizing that we tend to learn most when we find that generally accepted hypotheses can no longer be sustained. By coproducing knowledge about the river environment, we have the opportunity to challenge existing hypotheses (academic or lay), to produce new knowledge and so to move beyond the impasse that can follow where public engagement relies upon deliberation over

one set of experts' reports (for a related example, see Lane *et al.* [2011] for how this was undertaken in relation to flood risk management).

Given the shift within some western societies toward new forms of more upstream or democratic decision-making, and the recognition of coproduction as a means of doing this, river restoration practitioners will have increasingly to embark upon public engagement activities and research is needed to test different ways through which coproduction may be achieved. This will need to include reflection upon who should be involved in public engagement [Harrison and Mort, 1998; Rayner, 2003; Junker *et al.*, 2007; Stirling, 2008] and who should set restoration objectives, which may not always be evident, especially if river restoration is being attempted over larger spatial scales and where there will be a greater range of "publics" to engage [Maynard, 2013]. There is also a possible threat to river restoration that follows from these new forms of democratic decision-making, if human-centric concerns become dominant and if we do not also research how key parts of an ecosystem can and should be represented during public engagement (e.g., who speaks for a "fish," and how). Such research will require a deeper involvement of the social sciences and humanities in river restoration research.

5.3. Challenges for Scientific Understanding in River Restoration

Compounding the socioeconomic and other challenges for implementing river restoration discussed above are persisting gaps in scientific understanding of the ecological and physical processes, and of the feedbacks among them, fundamental to river restoration. The need to understand how different aspects of physical complexity assist or result in biogeochemical function, stream metabolism, stream ecosystem productivity, and contaminant degradation is particularly pressing. Although correlations between physical complexity and ecological function have been hypothesized [Pinay *et al.*, 1999; McClain *et al.*, 2003; Craig *et al.*, 2008], research has mostly focused on differences between physically more or less complex river segments rather than on quantitative predictions of how increasing complexity equates to predictable increases in specific measures of ecosystem function. Different forms of complexity have been shown to increase nutrient retention and uptake [Gooseff *et al.*, 2007; Roberts *et al.*, 2007; Baker *et al.*, 2012; Tuttle *et al.*, 2014]. Studies of restored river reaches indicate, however, that the effects of greater physical complexity on the abundance and diversity of riparian and aquatic organisms are ambiguous [Huryn and Wallace, 1987; Muotka and Laasonen, 2002; Lepori *et al.*, 2005; Palmer *et al.*, 2010a, 2010b; Wyżga *et al.*, 2012b], either because the restored complexity did not facilitate the required ecosystem processes or because other, unknown constraints limited ecological response.

In this context, there is a great need to characterize response curves of different river components that can facilitate modeling of system responses to either planned manipulation or unplanned human or natural disturbance. Response curves illustrate the response of a particular physical or biotic variable such as water temperature to changes in a control variable such as discharge or riparian shading (Figure 4) [Vanderpoorten

and Durwael, 1999]. Operators of hydroelectric dams can predict exactly what modified flow releases from the dam will cost in terms of lost revenue generation, for example, but river scientists typically cannot predict exactly what benefits will result in terms of greater recruitment of fish or riparian vegetation. Although prediction of river system changes will never be as precise as economic analyses because of equifinality and contingency in river ecosystems, recent research indicates the enhanced predictive ability that can result from development of response curves [Arthington *et al.*, 2006; Merritt *et al.*, 2010; Shafroth *et al.*, 2010]. King and Brown [2010] review several basin-scale flow assessment projects in Africa and southeastern Asia that incorporated response curves to predict physical and biotic components of river ecosystems likely to result from specified flow regimes. In the flow assessment for the Okavango River basin of southern Africa, more than 4000 individual response curves were incorporated into a Decision Support System known as DRIFT (Downstream Response to Imposed Flow Transformation) to evaluate the river ecosystem response to diverse scenarios of flow regulation [King *et al.*, 2014]. Response curves could also be very useful in determining where and when restoration is likely to have a significant beneficial effect on stream ecology or water quality, and the conditions under which it will not.

There are at least two basic challenges in using response curves. The first is to quantify the relationship between control variables such as physical channel complexity or flow regime and response variables such as water quality or biological community characteristics, as discussed above. The second is to understand the limitations in applying the response curve. As a hypothetical example, greater channel complexity could enhance nitrate removal by 50%, but anthropogenic increases in nitrate loading could negate this improvement. Or environmental flow releases could significantly increase habitat availability for native fish, which nonetheless fail to recover because of competition from introduced species. Limitations beyond the scope of most river restoration projects may help to explain many of the documented restoration failures [Bernhardt and Palmer, 2011; Doyle and Shields, 2012; Roley *et al.*, 2012a].

Inherent in the concept of response curves is the ability to quantify how the extent and location of restoration influence ecosystem function. For example, significant buffering by riparian zones of sediment and nitrate fluxes to channels is likely to require some minimum proportion of channel length, minimum buffer width, and specific ecological characteristics (e.g., plant community composition, soil composition) [Baker *et al.*, 2006; Weller and Baker, 2014]. Thresholds in system function appear to characterize many aspects of physical and ecological form and process in rivers [Shafroth *et al.*, 2010], and response curves can be used to identify potential thresholds critical to ecologically successful restoration.

Another basic challenge is to identify all of the relevant dimensions of the site-specific context. For example, flow regime is an important master variable that drives river ecosystem function, yet restoring natural range of variability in flow regime [Poff *et al.*, 1997] may not restore ecological function if other constraints such as altered sediment regimes [Wohl *et al.*, 2015], channel engineering, or invasive organisms limit river ecosystem response [Pasternack, 2013]. A vital component of context is watershed-scale effects such as highly altered inputs of water, sediment, nutrients, and contaminants from uplands and tributaries into the main channel. Although several review papers identify watershed-scale effects as a dominant limitation to restoration in many rivers [e.g., Bernhardt and Palmer, 2011; Doyle and Shields, 2012], there is little consensus on how to effectively identify or mitigate these effects and only a small percentage of restoration projects include watershed-scale action [Palmer *et al.*, 2014b].

An additional challenge for river restoration is the large, and perhaps expanding, gap between knowledge of processes such as sediment transport, as developed in physical experiments and numerical models, and our ability to use that knowledge for prediction and/or measurement within real rivers in the context of restoration. Wohl *et al.* [2015] discuss some of the reasons for this gap, including lack of spatially extensive or long-term measurements of sediment discharge on most rivers, the expense and logistical difficulty of measuring sediment transport, especially bedload, in rivers, and the substantial spatial and temporal variability in sediment movement within river corridors. River restoration remains constrained as well by limitations in our fundamental understanding of sediment dynamics and in methods for estimating sediment supply [Wilcock, 2012].

An emerging trend and challenge in river restoration is increasing appreciation of the importance of incorporating climate change considerations and resiliency into restoration planning [Beechie *et al.*, 2013]. Climate change may be accounted for in restoration in multiple ways: recognition that recent stream flows

may not be representative of future flows (e.g., for determining channel capacity), increased emphasis on creating thermal refugia, and emphasis on restoration methods that will be resilient to or mitigate climate change [Beechie *et al.*, 2013]. Moreover, climate change concerns have driven a profusion of studies investigating the vulnerability of various fish species to climate change-related changes in flows, stream temperatures, and hydrologic connectivity [Wenger *et al.*, 2011; Wade *et al.*, 2013; Jaeger *et al.*, 2014]. Such studies provide potential guidance for basin-scale restoration planning and prioritization.

5.4. Changes in River Restoration Within the Past Decade

In the decade since publication of Wohl *et al.*'s [2005] paper on river restoration, we note several ways in which river restoration has changed, beyond those identified in section 3. These include: increasing use of stream mitigation banking; development of new tools and technologies that facilitate acquiring and manipulating information on river process and form; growing recognition of the importance of biological-physical feedbacks in rivers; and more effective communication between practitioners of river restoration and the river-science research community.

Stream mitigation banking (SMB) allows developers to offset alteration of streams by purchasing credits through stream restoration at other sites. First developed by the U.S. Army Corps of Engineers in 2000, the practice is spreading within the USA, despite the lack of consistent criteria for defining a "stream mitigation unit" [Lave *et al.*, 2008, 2010]. North Carolina has one of the most developed programs in the USA and this program focuses on quantity in terms of length of stream and quality in terms of geomorphic characteristics, with no requirements for ecological assessments [Lave *et al.*, 2008]. The development of SMB has provided a new impetus for stream restoration, but it also represents a major shift in the drivers of river restoration where developers are no longer forced to restore rivers impacted by their development regardless of how much this might cost [Lave *et al.*, 2010]. Rather, a developer can avoid directly having to engage in restoration by purchasing credits that other restoration projects have acquired [Lave *et al.*, 2010]. Lave *et al.* show how this trading relies heavily upon the idea that destruction of a certain length of channel of a particular type can be countered by the purchase of credits for a certain length of channel of the same type somewhere else. In states where SMB is now commonplace, this practice is reinforcing a particular type of restoration that does not accurately capture the range of ecological characteristics destroyed in one river or restored in another [Lave *et al.*, 2010]. Evaluation will be needed of the impacts of market penetration into an activity that in general has been dominated by the academic and public-sector natural science, with occasional extension into broader nature-society interfaces, as we show above. Indeed, Lave *et al.* [2010] argue that if this market penetration continues, and given the dependence of markets upon simple and clear metrics, river restoration is going to be increasingly blind to the kinds of scientific developments we have reviewed in this paper.

Emerging tools and technology applicable to research on rivers have been increasingly applied to restoration. Our ability to measure topography has expanded greatly as a result of airborne and terrestrial lidar [Hauer *et al.*, 2014], multibeam bathymetry [Lejot *et al.*, 2007], drones, and structure-from-motion photogrammetry [e.g., Fonstad *et al.*, 2013]. Topographic measurements with improved temporal and spatial resolution have contributed to restoration planning, detection of geomorphic change for monitoring [Wheaton *et al.*, 2010], and multidimensional morphodynamic modeling using high-resolution topography [Pasquale *et al.*, 2011] to guide restoration [Wilcock, 2012].

In addition to monitoring biotic response to physical manipulations of water or sediment fluxes or channel geometry, river restoration and practice increasingly include explicit recognition of and, in the case of restoration practice, reliance on, physical-biotic interactions that drive fluvial processes and restoration of desired conditions (Figure 5) [Gurnell *et al.*, 2012]. For example, simple, ecologically based restoration approaches taking advantage of the ecosystem engineering provided by beaver have been proposed and implemented, such as the use of beaver dam analogues to restore incised streams [Pollock *et al.*, 2007, 2014; DeVries *et al.*, 2012]. The use of flow releases to promote recruitment of desired native riparian vegetation [Rood *et al.*, 2003] and/or scour of undesired species [Wilcox and Shafroth, 2013] present a contrast to restoration approaches focused on plantings or mechanical vegetation removal. Dam decommissioning in Fossil Creek, Arizona, USA triggered a set of ecogeomorphic feedbacks associated with regrowth of travertine steps, producing rapid and dramatic restoration of physical and ecological processes [Fuller *et al.*, 2011].

A final recent development in river restoration is improved communication between river scientists and practitioners of river restoration. As restoration practice accelerated during the 1990s and early 2000s, a gap

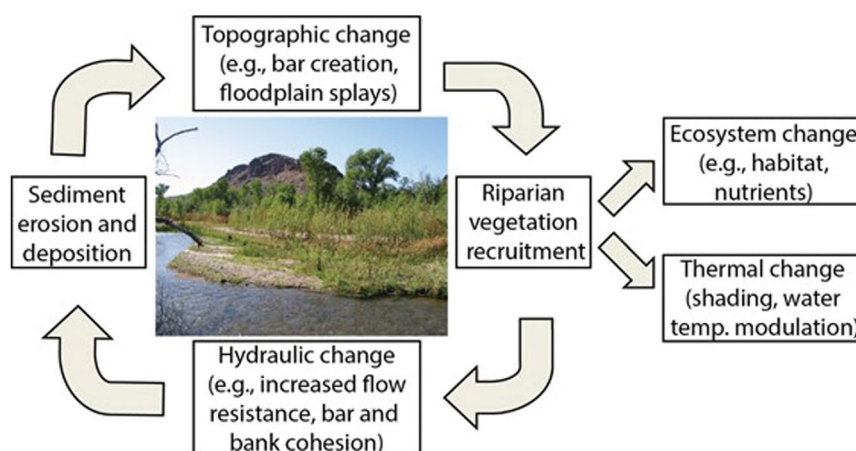


Figure 5. Conceptual diagram illustrating one set of potential ecogeomorphic feedbacks associated with restoration of high flows in hydrologically altered rivers, where reintroduction of floods can produce sediment transport and deposition and associated geomorphic changes that can create colonization sites for riparian vegetation. Recruitment of riparian vegetation can in turn produce hydraulic changes that alter velocity fields and sediment deposition patterns, resulting in feedbacks to geomorphic processes, as well as ecosystem and thermal changes. Center photo shows riparian seedlings recruited following environmental flow release on the Bill Williams River, Arizona.

between research scientists and practitioners developed [Wilcock, 1997]. Within the USA, researchers published numerous critiques of Natural Channel Design (NCD) methods and calls for process-based restoration [e.g., Simon *et al.*, 2007], prompting defenses of NCD and claims that the ivory tower misunderstood common restoration practices [e.g., Rosgen, 2008]. Although NCD remains the most widely accepted practice for the restoration of shallow streams in the USA [Lave, 2009], the persistent divide between researchers and practitioners [Cockerill and Anderson, 2014] has narrowed in some respects. Rhetoric regarding restoration science and practice, as played out in journal papers, replies, and counter-replies, has cooled, perhaps reflecting fatigue and/or recognition of common ground [Lave, 2009, 2012]. Academics have moved beyond only writing critiques, to seeking to provide tools and training that aim to link river science and restoration practice [Lave *et al.*, 2010; Wilcock, 2012]. The availability of process-based training in stream restoration, for example via university-sponsored restoration short courses and professional degree programs, has expanded [Schmidt, 2008; Niezgoda *et al.*, 2014]. Professional meetings (e.g., River Restoration Northwest) have served as effective fora for connecting researchers and practitioners. Applied research directed toward informing stream restoration has expanded, including laboratory experiments linked to stream restoration, construction of full-scale flume facilities oriented toward addressing restoration questions and problems [Wilcock *et al.*, 2008; Singh *et al.*, 2013], and development of morphodynamic models to guide restoration [e.g., McDonald *et al.*, 2010]. Researchers have also sought to provide tools accessible to practitioners for addressing challenging issues such as addressing uncertainty [Wheaton *et al.*, 2008; Wilcock, 2012], estimating sediment fluxes [Pitlick *et al.*, 2009], and identifying river segments amenable to specific types of restoration, such as what Wheaton refers to as the “cheap and cheerful” approach [Wheaton, 2013] of reintroducing beaver (*Castor* spp.) to historically occupied river habitat in North America [Macfarlane *et al.*, 2014] and Europe [John and Klein, 2004].

Some of the criticisms levied by academics have, to some degree, been absorbed into stream restoration practice. For example, evaluation of restoration through monitoring, the absence of which was a target of criticism, remains generally inadequate but has become more frequent. This may be especially true of larger-scale restoration projects such as the Provo River restoration [Erwin *et al.*, 2012] and the channel reconstruction following the removal of Milltown Dam on the Clark Fork River, Montana [Montana, 2008]. Many of the challenges surrounding monitoring persist, however, including insufficient funds and monitoring that, where present, may focus exclusively on detecting deviation from design guidelines rather than on whether geomorphic and ecosystem processes have been restored, which can require different types of baseline data [Downs *et al.*, 2011]. Indeed, Morandi *et al.* [2014], in the evaluation of 44 French river restoration projects, showed that most positive conclusions regarding river restoration tended to be associated with the weakest evaluation strategies. Further, Kurth and Schirmer [2014] showed, in a consideration of 848

Swiss restoration projects, that even if there was a clear evaluation strategy, the success of a project depended on how success was defined in the first place.

One challenge to the expansion of monitoring is the lack of appetite among researchers, who may be more focused on developing new process knowledge, for participating in monitoring, which may involve multi-year field campaigns with minimal publication return and minimal funding. There are notable exceptions, including contributions by researchers to developing standardized monitoring protocols, such as the Columbia Habitat Assessment and Mapping Program (CHAMP) [Bouwes *et al.*, 2011; Wheaton *et al.*, 2012] or NOAA's River RAT program [https://www.webapps.nwfsc.noaa.gov/apex/f?p=275:1; Skidmore *et al.*, 2012], and to applying advanced instrumentation to monitoring [Schneider *et al.*, 2011]. The more pervasive inadequate monitoring of indicators of restored ecological function, however, means that although adaptive management remains a popular concept, it is not actually being implemented on most restoration projects.

Adaptive management has typically been applied to large-scale reconnection efforts such as experimental floods in Grand Canyon [Melis, 2011] or restoring more natural water distribution patterns in the Everglades [LoSchivo *et al.*, 2013] rather than reach-scale reconfiguration projects. In some of these large projects adaptive management has led to useful advances in scientific understanding and practical management. However, Olden *et al.* [2014] found that most experimental flow releases focus on a single biological variable (primarily fish) rather than ecosystem processes and only a third of experimental flow releases are repeated, even though management objectives are more than four times as likely to be achieved when ongoing experimentation with flows (i.e., adaptive management) occurs.

Key gaps remain in approaches advocated by researchers and those commonly implemented by practitioners. These include differences in the emphasis on understanding sediment balances [Wohl *et al.*, 2015], recognition of ranges of variability in geomorphic form and process, the applicability of reference reaches and the bankfull discharge as guiding design criteria, and a continued emphasis in restoration practice on grade control, bank stabilization, and other structural approaches [Doyle *et al.*, 2007; Wilcock, 2012].

6. Concluding Remarks

The diverse forms of river restoration currently being practiced provide a testing ground for both scientific understanding of rivers, and societal attitudes toward rivers and humanity's ability to sustain river ecosystems. River restoration has been undertaken with many purposes. A primary one, recreating the past, is commonly not possible, either because the environmental context that resulted in former river processes and forms no longer exists, knowledge of past river conditions is insufficient to underpin restoration, or river systems follow complex trajectories that commonly make it impossible to return to a previous state [Dufour and Piégay, 2009]. Absent the ability to return to some condition present prior to human alteration of a river corridor, river restoration has the potential to enhance the self-maintaining character of a river and the potential to provide ecosystem services such as flood control, nutrient retention, clean water, and biodiversity. As numerous case studies and synthesis papers make clear, however, such effective river restoration requires recognition of physical and ecological processes, diverse forms of connectivity within river networks, physical-biotic interactions, place-specific history and complexity [Brierley and Fryirs, 2009; Dufour and Piégay, 2009; Fryirs and Brierley, 2009], and collaboration between river scientists and restoration practitioners. Increasing emphasis on ecosystem services also has the potential to encourage restoration projects to focus on a subset of processes that create a desired service rather than on the entire river ecosystem and to treat symptoms rather than underlying problems [Palmer *et al.*, 2014a]. To date, the majority of river restoration projects do not satisfy the central criteria of Palmer *et al.* [2005] for ecologically successful restoration. These criteria are that ecological condition must be measurably improved and the river ecosystem must be more self-sustaining and resilient to external perturbations so that only minimal postrestoration maintenance is necessary. Issues surrounding the social meaning of restoration projects are rarely considered, even though they may be dominant in achieving implementation in systems where communities have a say in how their environments are managed.

As a broad generalization, our survey of river restoration suggests that reconnection efforts are more likely to be successful than reconfiguration efforts. Numerous syntheses and meta-analyses suggest that reconfiguration efforts, which commonly focus on the reach-scale, fail to effectively restore river functional integrity with respect to water quality and biological communities [Bernhardt and Palmer, 2011; Violin *et al.*, 2011;

Doyle and Shields, 2012; Palmer and Hondula, 2014; Palmer et al., 2014a; Smucker and Detenbeck, 2014]. How much of this failure stems from ineffective restoration of form, and how much from watershed-scale processes such as increased nutrient loading or limited biological connectivity that overwhelm the effects of reach-scale form, remains unclear. Community participation in reach-scale, form-based reconfiguration of rivers can enhance public awareness of and commitment to rivers, but the restoration process may instill a false sense of accomplishment or complacency if ecological function is not restored. One of the implications of the lack of success in many reconfiguration projects is that this type of project is most likely to be used in stream mitigation banking, contributing to accelerated loss of ecologically functional streams.

Successful reconnection efforts include restoring flow regime [Tonkin et al., 2008], physically reconnecting main channels with floodplains or secondary/backwater channels [Ogston et al., 2015; Theiling et al., 2015], reintroducing natural ecosystem engineers such as beaver [Albert and Trimble, 2000; Pollock et al., 2014], and removing barriers such as dams [Poulos et al., 2014]. Reconnection-based restoration that focuses on restoring physical connectivity among the channel, floodplain, and hyporheic zone and restoring natural range of variability in flow and sediment regimes can be more effective in restoring ecological function, but requires explicit consideration of details such as the location, magnitude, duration, and timing of fluxes and the existence of thresholds in river ecosystem response.

The primary limitations to either reconnection or reconfiguration efforts are not scientific understanding of physical and ecological processes in rivers, however. Our review suggests that widespread inability to restore full river function and ecological communities comparable to reference conditions reflects two primary constraints. The first is the divergence between scales of alteration and scales of restoration. Restoration projects typically do not address basin-scale changes in water, sediment, nutrient, and contaminant inputs to rivers and basin-scale changes in longitudinal, lateral, and vertical connectivity in rivers. Reach-scale restoration efforts are particularly likely to be insufficient where the majority of the drainage basin has been altered, but even basin-scale efforts that focus on a single variable such as flow regime, rather than considering the full suite of variables that influence river ecosystems, are likely to be of limited success. The second primary constraint is the sometimes substantial gap between society's expectations of rivers, which may be largely esthetic, and scientific understanding of rivers as dynamic systems that require some level of disturbance and as ecosystems with numerous largely invisible functions such as hyporheic exchange. This gap can result in societal support for cosmetic restoration efforts rather than acceptance of the importance of maintaining variable inputs and river form, such as those associated with floods. Although as scientists we need to continue to develop our fundamental knowledge of river process and form, the constraints imposed by basin-scale changes and societal expectations suggest that we need to put equal emphasis on education and outreach connected with river restoration.

River restoration has moved to the forefront of applied water-resources science during the past 50 years, enhancing public awareness of rivers as complex ecosystems in which carefully designed human interventions can potentially restore environmentally beneficial processes and aquatic and riparian communities. We still have a long way to go, however, in mitigating the continuing rapid and widespread loss of rivers as ecosystems that is occurring globally. Continued development of the research community's ability to measure, simulate, and work with river systems, and to collaborate with society in understanding and managing rivers, can only benefit rivers and humanity.

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