Chapter 136

Wetland and River Restoration

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ABSTRACT

Ecosystem functions and services performed by wetlands and rivers have been significantly diminished at a global scale. As societies become increasingly aware of and dependent upon life-sustaining services provided by these ecosystems, an increased emphasis on ecological restoration will likely become essential for provision of critical services and goods including clean air and water, food, and climate regulation. Yet, progress in advancing the effectiveness of ecosystem restoration has been hindered by many factors including oversimplification of wetland and river dynamics, ignoring multiscale factors that limit project potential, and a persistent communication gap between the scientific and practitioner communities. This chapter provides a brief overview of the broad and complex field of stream and wetland restoration with the aims of: (1) defining wetland and river restoration, (2) describing key elements of restoration activities that increase the likelihood of success, (3) listing some of a wide range of established techniques, and (4) providing context on the advancement of wetland and river restoration as a science and practice.

136.1 INTRODUCTION

Ecosystem functions and services performed by wetlands and rivers have been significantly diminished at a global scale. For example, 80% of wetland area across Europe has been lost in the past millennium, and in the United States (U.S.), over half the wetlands existing at the time of European colonization have been lost (Verhoeven, 2014; Mitsch and Gosselink, 2015). The economic growth resulting from vast programs of wetland drainage and river channelization performed to expand agriculture and provide navigation and "flood control" has been accompanied by the degradation of water quality, wildlife habitat, and floodwater storage functions at continental scales. Similarly, approximately half of U.S. streams and rivers are not suitable for water supply, aquatic life, or other designated uses, such as fishing or swimming [Environmental Protection Agency (EPA), Watershed Assessment, Tracking & Environmental Results; http://ofmpub.epa.gov/waters10/attains_nation_cy.control#STREAM/CREEK/RIVER]. Wetlands and rivers are some of the most imperiled ecosystems on the planet and the ongoing trend of degradation is expected to have serious repercussions for human health and well-being in the coming decades (Millennium Ecosystem Assessment, 2005).

Over the past few decades, ecosystem restoration and ecological engineering have emerged as attractive means of countering the loss of aquatic and riparian ecosystem functions and services. Successful ecosystem restoration projects have been carried out at a variety of scales across several continents. As societies become increasingly aware of the value of life-sustaining services provided by ecosystems, stream and wetland restoration has evolved into a multibillion dollar enterprise, with stream restoration expenditures exceeding $1B per year in the U.S. alone (Bernhardt et al., 2005). Despite the ubiquitous practice of river and wetland restoration, its success in reestablishing critical aquatic ecosystem functions and services remains generally dubious [e.g., Doyle and Shields (2012)], and net improvements that are documented may come at the expense of large inputs of nonrenewable energy. Detractors also argue that aquatic ecosystem restoration should be pursued with caution because projects often lack clear objectives and adequate underpinning in scientific theory and knowledge, are often applied at ineffective scales (site/reach scale) given the function(s) claimed to be restored, and lack adequate monitoring to ensure restoration goals have been met (Bernhardt and Palmer, 2011; Moreno-Mateos et al., 2012).

Progress in improving both the scientific basis and practical effectiveness of ecosystem restoration has been hindered by many factors including oversimplification of wetland and river dynamics, ignoring upstream and watershed-scale factors that might limit project potential, a "build it and they will come" mentality regarding aquatic habitat, as well as a persistent communication gap between the scientific and practitioner communities. This gap has arisen in part from policies of compensatory mitigation, that is, the restoration, establishment, enhancement, or preservation of wetlands, streams, or other aquatic resources, for the purpose of offsetting unavoidable adverse impacts to wetlands and rivers. Such policies may potentially dis-incentivize transparent disclosure and analysis of uncertainties, and the design of effective monitoring programs aimed at improving understanding of the long-term performance of restoration activities (Palmer et al., 2007).

Despite these criticisms, an increased emphasis on ecological restoration will likely become essential for provision and restoration of critical ecosystem services and goods including clean air and water, food, and climate regulation from ongoing and historic impacts. Strategic wetland and stream restoration activities have the potential to counteract five principal categories of threat to fresh waters: (i) overexploitation, (ii) water pollution, (iii) fragmentation, (iv) destruction or degradation of habitat, and (v) invasion by non-native species.

Given the breadth and complexity of stream and wetland restoration, we only attempt to provide an overview in this chapter. Specifically, we aim to: (i) define wetland and river restoration, (ii) describe key elements of restoration activities that increase the likelihood of success, (iii) list some of a wide range of established techniques, and (iv) provide context on the advancement of wetland and river restoration as a science and practice. As restoration of natural systems requires an in-depth understanding of physical and biological components and processes; readers are encouraged to consult primers on wetlands (e.g., Mitsch and Gosselink, 2015), fluvial geomorphology (e.g., Knighton, 1998; Wohl, 2014), stream ecology (e.g., Allan and Castillo, 2007), hydrology (e.g., Gordon et al., 2004; New Jersey Department of Environmental Protection, 2008), sediment transport (e.g., Wilcock et al., 2009), and watershed restoration (e.g., Williams et al., 1997; Roni and Beechie, 2012).

136.2 DEFINITIONS

Ecological restoration may be generally defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (Society for Ecological Restoration International Science & Policy Working Group, 2004). Wetland restoration focuses on actions that result in the reestablishment of ecological processes, functions, and biotic/abiotic linkages, that lead to a persistent, resilient ecosystem that is integrated within its landscape (Brown, 2000). Similarly, river restoration has been defined as assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system and replacing lost, damaged, or compromised elements of the river system (Wohl et al., 2005). Although restoration is difficult to define precisely, there are several key characteristics that may distinguish it from rehabilitation and naturalization, which differ from restoration in terms of scale and processes addressed (Fig. 136.1). Active restoration involves direct manipulation or intervention within a stream or wetland. Passive or indirect restoration might involve the reestablishment of a key process, such as removing a stressor such as fencing cattle from direct contact with a stream.

136.3 THE RESTORATION PROCESS

While it is not possible to anticipate every possible combination of goals, context, and history, there are general principles of science and engineering that should be applied to every restoration project. These principles lead to decision-making methods that can be used to identify useful alternatives and evaluate the tradeoffs among them in an open, transparent fashion. Several references describe step-by-step approaches to stream and wetland restoration [e.g., Natural Resources Conservation Service (NRCS; 1997; 2007)], some of which are well detailed and comprehensive (Jacobson and Berkley, 2011). Table 136.1 provides a summary of essential steps and principles in the restoration process.

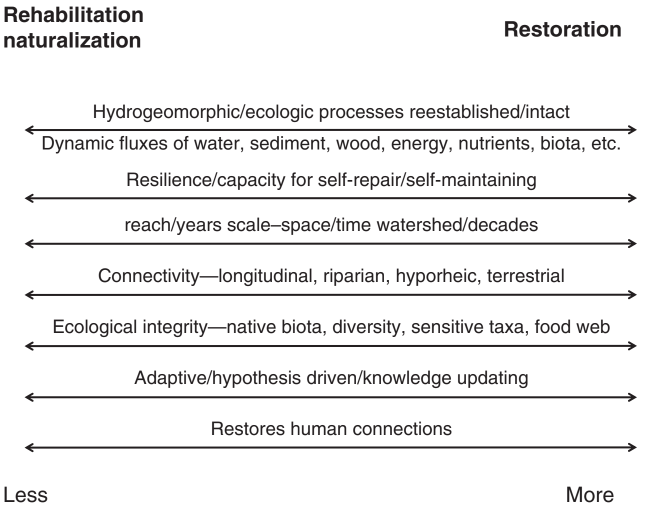

Figure 136.1 Spectrum of processes and features of actual wetland and river restoration versus rehabilitation or naturalization.

Table 136.1 Restoration Process Essential Steps and Principles Overview

No.	Step	Context	Key questions	References
1	**Identify and refine restoration goals**	Restoration goals express broad, holistic desires as opposed to local or watershed restoration actions later derived from these goals. Often suites of actions, grouped as alternatives, can meet a single restoration goal.	• What is motivating this potential restoration? Is it a regulatory mandate, aesthetics or possibly the restoration of an ecosystem function? • How can the initial goal(s) be modified to provide broader ecosystem benefit?	• Bateman et al. (2012) • Wohl et al. (2005) • Hallett et al. (2013)
2	**Identify interested parties (stakeholders)**	Successful projects often require multiple motivations and funding sources; the breadth of stakeholder experience increases the likelihood of catching and proactively addressing challenges. Broad-based participation helps ensure that self-interest or agency agendas do not drive the process from the top down and helps avoid challenges by those not involved from the start.	• Who has an interest in this system or the initial goal? • How do you get interested parties involved? • What will be the role of the stakeholder group through the various stages of the project? Will they have decision-making authority? • How and when will you communicate with stakeholders?	• Harter et al. (1998) • Schkade et al. (1996)
3	**Identify problems and opportunities, constraints, and sources of funding**	While restoration projects are usually initiated in response to a singular concern, each project should be viewed as an opportunity to address a breadth of concerns. By embracing the multiple dimensions of restoration, multiple problems and opportunities can be identified. With this broader base, the project may be able to leverage more funding sources, have broader buy-in, and generally be more successful.	• How is the system currently being used? How might this use change over time? • What comes into or out of the system? For example, sediment, fish, birds may pass through the system but not reside there. • Who might have funding to address some of these problems and opportunities?	• Naiman et al. (2012) • Suding et al. (2004)
4	**Develop an understanding of the watershed context**	Watershed-scale physical drivers interact with local constraints to inform restoration objectives. Drivers include: hydrology, sediment flux, ecosystem processes and socio-economic factors such as land-use. The legal context of the project should also be considered including the various local, state, and federal regulatory requirements.	• Is water quality impaired? • Is the watershed hydrology flashy or consistent? • Has land use changed or will it be changing? • What kind of fish, amphibians, and mammals live in the system? Are there invasive or exotic species? • What might be the source of pollutants or channel instability in the watershed?	• Smith et al. (2011) • Wohl et al. (2005)
5	**What restoration scale is appropriate to meet the goals?**	The watershed context from No. 4 can help identify if the root of the problem is local, distributed across the watershed, or can be traced to a single point upstream. Goals, problems, and opportunities can then be tailored to local or watershed-scales.	• Can the restoration goals be addressed with a local-scale project? • Should efforts be focused in the watershed instead of the stream corridor? • Is there a better location for the restoration project considering problems and opportunities? • Have your restoration activities been integrated with other restoration activities on multiple spatial and administrative scales?	• Bohn and Kershner (2002) • Moreno-Mateos and Comín (2010)
6	**Develop appropriate objectives**	Objectives should define the response you wish to invoke by making changes within the system. These are not specific actions but rather quantifiable changes in the system that the design will produce. Properly selected objectives will direct restoration actions and determine how actions are combined into alternatives.	• Are objectives attainable for the given system? • Are they measurable? Will you be able to identify the resource and trait to be measured and the anticipated direction and magnitude of change?	• McKay et al. (2012)

No.	Step	Context	Key questions	References
7	**Define metrics of success**	Metrics are measurements of how well objectives have been met and thus quantify the success of the stream restoration project. Effort put into selecting appropriate metrics will be paid back in a transparent decision analysis process.	• Are direct metrics or proxy metrics more appropriate (i.e., dissolved oxygen vs. water temperature)? • Have your metrics specified a level of precision, anticipate power to detect change, and an anticipated level of change?	• McKay et al. (2010)
8	**Determine necessary level of design effort**	There are a broad hierarchy of tools for assessment and design available. Project success hinges both on the type of site you are working on and the type of restoration that has been proposed. More complex design with multiple structures may be more risky.	• Is my project and chosen site inherently high or low risk? • What types of tools and data are available for this type of project design?	• Skidmore et al. (2011)
9	**What suites of actions are available to address each restoration objective?**	Identify and package the actions which will meet the list of the restoration objectives. Strive to develop a full spectrum of possible actions, not just the obvious ones. At this point, maintain the breadth of alternatives by evaluating substantively different approaches.	• What are some other ‘outside the box’ type actions which will meet my objectives? • Are there adaptive actions which would be appropriate? If so, what type of monitoring would be needed to support this decision? • Are there objectives which are in direct conflict with each other?	• Keeney (1996)
10	**Score performance of alternatives for each objective, incorporating uncertainty**	Once alternatives have been generated, their performance can be evaluated in the context of cost effectiveness and stakeholder desires. For example you could use a Multi-Criteria Decision Analysis (MCDA) approach which takes into account the progress toward multiple objectives along with the stakeholders’ preferences and regulatory or budgetary requirements.	• How long will each alternative take to achieve the project objectives? • Has uncertainty from data been propagated through models, to model output? • Will additional study reduce uncertainty?	• Suedel et al. (2011) • Wissmar and Bisson (2003)
11	**Use alternative performance, professional judgment, and constraints to select final design**	While the alternative scoring process provides valuable information, it is not the final word in the decision-making process. There are times that an alternative scores quite well for all objectives, but due to constraints, is not feasible.	• How can alternatives be adjusted to improve performance on one objective without diminishing performance on another?	• Suedel et al. (2011) • Suding et al. (2004)
12	**Prepare final design, including plan for permitting and monitoring**	This is the traditional step in the design process. Given the previous steps, objectives and constraints have been laid-out, an alternative has been selected, and it is now time to use the necessary analytical tools to design the restoration.	• Given what has already been done and the knowledge of the system; what is the appropriate design effort for the final design?	• NRCS (2007)
13	**Implement project design**	A well-orchestrated restoration plan is a necessity for both passive and active restoration. Implementation can be timed and carried-out in ways to minimize harm to the existing ecosystem and information learned during construction can help inform modifications and future designs.	• How can the construction be carried-out to minimize harm to the ecosystem? Consider seasonality, flow regime, spawning and migratory windows, and other ecosystem properties.	• Palmer et al. (2005)
14	**Learn from the project (implement, learn, and act based upon monitoring)**	Not every restoration project requires monitoring, but monitoring should be considered early and throughout the planning process as it can fundamentally alter restoration designs and decisions. To aid in the design of a monitoring plan, specific questions and data needs must be established.	• Are there opportunities to adaptively adjust the implemented work based on monitoring observations? • How are the monitoring objectives related, but different from the project objectives? • Are observed values of metrics consistent with assumptions, hypotheses, and predictions made in No. 7?	• Ralph and Poole (2002)

136.4 APPROACHES TO WETLAND AND RIVER RESTORATION

136.4.1 The Hydrogeomorphic Setting

The structure and functions of wetland and riparian ecosystems are fundamentally controlled by hydrogeomorphic context, that is, interactions among geomorphic setting, water sources, and hydrodynamics (Brinson, 1993; National Research Council (NRC), 2002; Naiman et al., 2010). Getting the hydrogeomorphic template “right” is a prerequisite for guiding biotic organization toward a target state. The master variable in wetland restoration is the hydrologic regime during the plant-growing season, and the most basic requirement of wetland restoration is to reestablish hydrologic and soil characteristics that are matched to target plant assemblages. Near complete turnover in wetland plant assemblages can occur over elevational gradients on the order of 10 cm as microtopography can result in significant differences in frequency and duration of saturation and inundation during the growing season (Bledsoe and Shear, 2000). Soil physical and chemical properties are also a key control on the organization of wetland plant communities, and can be difficult to disentangle from hydrologic regime because factors such as texture, organic matter content, and acidity are often strongly associated with elevation and hydroperiod. In coastal restoration projects, wetland position relative to tidal elevations and salinity levels are fundamental design variables.

Success in wetland and riparian restoration fundamentally hinges on providing the appropriate physical template for establishment and self-organization of propagules that arrive via wind, water, animals, and human intervention; and designs must be based on an understanding of the subtle linkages between hydrologic regime, soils, and plant community assemblages (Southwood, 1977; Mitsch and Jørgensen, 2003). In particular, “biological benchmarks” and surveys that quantitatively relate surface inundation, soil moisture, or water table dynamics in the growing season to plant species composition across microtopographic gradients are useful for informing designs (Bledsoe and Shear, 2000; Hoag et al., 2001). However, precise engineering of relationships between hydrologic

Table 136.2 Examples of Active and Passive Restoration Activities at Local and Watershed Scales

Scale	Passive restoration measures	Active restoration measures
Watershed	• Grazing management/revegetation • Reregulate system of reservoirs • Riparian aforestation to allow natural recruitment of wood and establish cover • Recolonization of top predators for trophic cascade and reduced riparian herbivory	• Stormwater best management practice (BMP) installation/retrofit • Low-impact design development • Dam removal or fish passage structures • Agricultural BMP programs • System-level plan for restoring connected and redundant habitats for fishes • Non-native species management programs
Local	• Riparian fencing • Reintroduction of beaver • Riparian aforestation to allow natural recruitment of wood and establish cover • Removal of drainage infrastructure for wetlands	• Plug ditches/remove drains • Planform manipulation • Grade control • Levee setback • Streambank stabilization • Riparian zone/wetland planting

regimes and plant communities is challenging and elusive, and designers should avoid "overengineering" with hydraulic structures and prescriptive planting requirements that leave little room for self-organization. Instead, quantitative hydrology-soils-vegetation relationships are most useful for designs that aim to provide appropriate hydrologic and soil characteristics and microtopographic variability while relying on self-organization of vegetation (Mitsch et al., 1998). Note that for some riparian species, such as plains cottonwood (*Populus deltoides*), the timing and intensity of flood disturbance controls recruitment (Mahoney and Rood, 1998).

Ultimately, restoration of wetland and riparian ecosystems requires much more than water, and factors, such as landscape setting, soil properties, topography, nutrient supplies, disturbance regimes, invasive species, seed banks, and declining biodiversity can constrain the restoration process (Zedler, 2000).

136.4.2 Process-Based Restoration

Wetland and river restoration projects should be considered through the lens of physical processes operating across nested scales of space and time (Frissell et al., 1986), and evaluated with a focus on addressing the root causes of degradation and not merely the symptoms (Mitsch and Jørgenson, 2003, Beechie et al., 2010, Kondolf, 2011). Process-based approaches to restoration encourage designers to consider the drivers at play in a system of interest and scale the restoration to address disruptions to these drivers and the "local potential" of the site (Beechie et al., 2010). If full or partial restoration of processes is not attainable, then mechanisms for long-term maintenance must be in place to ensure that reach- or site-scale stabilization or habitat improvement measures meet intended goals. An important caveat lies in the challenge of understanding reference conditions, which may be obfuscated by centuries of human influence on the landscape, resulting in the need to restore to a site's potential defined by the limitations of contemporary processes and land use (Wohl et al., 2005; Walter and Merritts, 2008; Hall and Zedler, 2010). The following sections and Table 136.2 contrast and discuss stream and wetland activities at watershed and local scales.

136.4.3 Watershed Scale Restoration

Physical and ecological degradation of rivers and wetlands often result from indirect impacts at the watershed scale. This may be due to many factors including hydrologic alteration, disruption in sediment continuity or excess sediment supply, chemical pollutants, and loss of lateral and longitudinal connectivity. The direct impacts of channelization and drainage may also play a dominant role at a watershed scale. Short-term, local-scale restoration activities can improve the condition of streams and wetlands, and are generally feasible under many different management settings; however, they are unlikely to produce permanent effects if they do not ultimately incorporate the reestablishment of essential watershed processes (Wohl et al., 2005; Roni and Beechie, 2012). Such actions include riparian fencing and planting, water-chemistry source control, fish-passage projects, and certain hydraulic structures. Short-term actions address acute problems typical to streams and wetlands in urban and agricultural watersheds; they are commonly necessary, but not sufficient, to restore biotic integrity.

In contrast, a watershed-scale understanding of how water, sediment, and other fluxes have been altered, and designing restoration projects that explicitly account for these new conditions, are essential for sustainable restoration.

It is important to recognize that stream and wetland restoration projects do not exist in isolation and they can significantly influence other parts of the watershed. Noting the integrative and sensitive nature of streams, the eminent river engineer Hans Albert Einstein (1972) said:

> "If we change a river we usually do some good somewhere and good in quotation marks. That means we achieve some kind of a result that we are aiming at but sometimes forget that the same change which we are introducing may have widespread influences somewhere else […] we must look at a river or a drainage basin or whatever we are talking about as a big unit with many facets. We should not concentrate only on a little piece of that river unless we have some good reason to decide that we can do that."

Restoration activities must be considered in their landscape context, not only for ensuring that the hydrogeomorphic setting is appropriate for sustaining the target ecosystem(s), but also to ensure that no harm is done to connected systems. For example, a channel-restoration project may successfully eliminate bank erosion and incision in a particular reach, but the reduction in sediment supply could subsequently cause instability and erosion in downstream reaches that become sediment starved. This underscores the importance of a systems perspective rather than a piecemeal amalgamation of individual restoration sites.

Analysis of the landscape context is also important for targeting restoration activities where they will be most ecologically effective. Geographic information systems provide a powerful platform for analyzing the connectivity and redundancy of physical habitats at drainage network scales (Doppelt et al., 1993; Jensen et al., 2001). Several schemes for identifying and prioritizing restoration activities at the watershed scale for maximizing water quality, hydrologic, habitat, and other benefits have been proposed (e.g., Richardson and Gatti, 1999; Roni et al., 2002; Williams, 2002; White Fennessy, 2005). It is critical that such prioritization schemes reflect the importance of headwater systems, which typically comprise the vast majority of stream length across the landscape (Leopold et al., 1964) and profoundly influence downstream water quality and quantity (Alexander et al., 2007).

Hydrologic Restoration

Dams and land use changes from urbanization and agriculture are the most widespread cause of hydrologic alteration (Allan, 2004; Poff et al., 2006). In urbanizing watersheds, impervious surfaces and/or compacted soils connected to stormwater collection systems efficiently route runoff to streams and wetlands where augmented quick flow volumes and peak discharges increase the erosive power of runoff resulting in sediment imbalance and a process of channel degradation (Booth, 1990). Watershed-scale efforts are required to address the root cause of this perturbation. In urban settings, these include disconnecting or retrofitting stormwater infrastructure, and low-impact design (Jaffe et al., 2010; In rural settings, agricultural soil conservation and tilling practices in conjunction with restoration and conservation of riparian buffers can mitigate hydrologic alteration (Brannan et al., 2001; Moore and Palmer, 2005).

Hydrologic alteration may also occur more directly from flow withdrawal or regulation. Human influences on the natural flow regime and associated impacts on aquatic ecosystems have gained attention in last few decades with the development of the environmental flow concept (Poff et al., 1997; 2010). Originally focused on estimating minimum seasonal flows for fish and aquatic macroinvertbrate habitat maintenance, the concept and management of environmental flows has expanded to incorporate aspects of a complete flow regime (Poff et al., 2010; Sanderson et al., 2012). Making connections between aspects of the flow regime and biophysical processes that support and maintain aquatic ecosystems have aided hydrologic restoration efforts (Mahoney and Rood, 1998; Whiting, 2002). Numerous examples now exist of conservation agencies and organizations partnering with reservoir managers to modify flow releases in support of fish recovery such as on the Green River (LaGory et al., 2012), sediment mobilization for spawning habitat (Viparelli et al., 2011; Meitzen et al., 2013), and floodplain and riparian wetland inundation (Vivian et al., 2014). Recent environmental flow efforts in the western United States have also explored mechanisms for leasing water from irrigators to augment base flows during low-flow periods and keep river segments from running dry (Connor et al., 2013; Lane-Miller et al., 2013).

Connectivity in Lotic Systems

Connectivity in lotic systems is a multidimensional problem concerning lateral, longitudinal, and vertical connections across multiple scales and is vital for sustaining key processes and well-functioning ecosystems (Ward, 1989;

Kondolf et al., 2006). Streams and rivers may become laterally disconnected from their floodplains due to construction of levees, floodplain development, channel incision, or indirectly by reduction of flood peaks from upstream flow regulation. Restoring lateral connectivity may involve physical removal of floodplain encroachments, manipulation of the channel to either raise the channel bed, excavation of a floodplain bench, restoration of flood hydrology via flow reregulation, or working with beaver.

Longitudinal connectivity, important from a biological and sediment-continuity perspective, is often artificially disrupted by hydraulic structures and imposed discontinuities in channel slope that create barriers to flows of organisms, propagules, and materials. These range from a small-scale road culverts or irrigation diversion weirs to large-scale dams. New guidelines from U.S. and state transportation agencies emphasize longitudinal connectivity in road crossing design (U.S. Forest Service, 2008; Hotchkiss and Frei, 2007). Restoring fish passage with dam removal, such as on the Elwha River, Washington (Wunderlich et al., 1994) and White Salmon River (Engle et al., 2013) has proven to be very successful. Fish bypass channels, ramps, and ladders are used when dam removal is not feasible. The science and design behind these engineered solutions is improving over time (Noonan et al., 2012). Vertical connectivity and hyporheic exchange can be enhanced by bedforms, wood, other instream features that create geomorphic complexity, and riparian vegetation plantings (Baker et al., 2012, Hester and Gooseff, 2010).

Water Quality and Ecological Integrity

Water quality restoration is most likely to be effective if focused on all major controls on ecological integrity (Karr, 1991; Karr and Chu, 1998):

- habitat structure
- flow regime/hydroperiod
- chemical water quality
- temperature
- energy sources
- biotic interactions

While the number of studies with sufficient data to confidently assess the performance of stream restoration projects is increasing, there is still comparatively little information for quantitatively evaluating the relative efficacy of different restoration methods for achieving specific aquatic life, nutrient reduction, or other water quality goals. The complexity of aquatic ecosystems and the significant variability among regions, watersheds, and sites further complicates comparisons. Despite these concerns, Palmer et al. (2014) reported success rates of various restoration methods in achieving various self-reported objectives. For example, riparian restoration provided the highest success in increasing nutrient uptake rates and reducing fluxes (88%), followed by in-stream structure installation (63%), wetland creation (25%), and channel reconstruction (14%). However, sample sizes were small and reported improvements were not necessarily statistically significant.

Addressing Other Stream and Wetland Fluxes

Hydrologic restoration in isolation may not fully address the root cause of degradation if other fluxes vital to physical, biogeochemical, and ecological processes in rivers and wetlands are not also concurrently addressed. Important fluxes include sediment (Schmidt and Wilcock, 2008; Wohl et al., 2015) as well as organic carbon (from large wood to dissolved organic matter) and nutrients in rivers and wetlands (Kayranli et al., 2010; Mutema et al., 2015). The Trinity River Restoration Program offers a good example of the paired relationship between hydrology and sediment flux. The Trinity Dam impounds water and sediment in northern California reducing the width and armoring tens of kilometers of river downstream. In an effort to restore native salmon habitat, a flow reregulation program has been established to release downscaled flood pulses. However, flood pulses alone would not address the armoring problem; therefore, augmentation of gravel and active channel restoration were also deemed necessary to induce geomorphic complexity and reduce channel armoring (Brown and Pasternack, 2008).

Sediment surplus may also be of concern. Common sources of excess, often fine, sediment are augmented hillslope erosion delivered through poor riparian buffers from agricultural practices, erosion from unpaved roads and their drainages (especially in managed forests), and incision and widening of channels due to hydrologic alteration. Both upland-focused and channel-focused restoration measures may be necessary to address the root causes of excess sedimentation (Reid and Dunne, 1996; Rosgen, 2007). In the latter case, sediment delivery from upstream channel instability may not be alleviated with mitigation of hydrologic alteration alone. Once channel change has initiated, it often follows a cycle of evolution until a new, stable slope and dimension is reached, unless river segment and reach-scale stabilization measures are taken (Schumm et al., 1984). In cases where channel form and the geomorphic setting has significantly changed due to the "ratchet effect" of vegetation encroachment (Tal et al., 2004) or other factors, restoring "natural" flows of water and sediment in the absence of mechanical interventions can potentially be counterproductive in terms of producing the habitat dynamics to which native biota are adapted. Thus, reestablishing sediment balance may be a more realistic and effective restoration strategy under contemporary constraints (Wohl et al., 2015).

136.4.4 Local-Scale Restoration

Due to limited resources or agency scope, restoration most often occurs at the individual site or reach scale to address acute instability or habitat quality issues (Bernhardt et al., 2005). When conducted in isolation, reach- or site-scale restoration may not address the root cause of aquatic ecosystem degradation; however, it can be effective when conducted as part of a watershed-scale plan (Palmer et al., 2005).

Morphology and Habitat Structure

Rivers: Habitat Enhancement with In-Channel Structures Placement of habitat features such as pools, boulder clusters, toe wood, and engineered log jams may not address root causes of habitat degradation (Platts and Nelson, 1985; Sudduth et al., 2011), but have been shown to increase local fish abundance and in some cases species richness (Shields et al., 2004; White et al., 2011). As previously discussed, wood historically played an important role in shaping river form and creating habitat complexity. Only recently have researchers and practitioners begun to highlight this role, study its benefits to river systems, and develop methodologies for successfully incorporating it into restoration design (Kail et al., 2007; Chin et al., 2008; Wohl, 2011). In systems where wood has been removed, often a threshold of large, stable wood along a reach is required before wood recruitment and self-sustainability can be achieved, especially in fine-bed systems (Shield et al., 2006).

Rivers: Approaches for Incised Channels Stream and riverine wetland restoration measures often target sedimentation and habitat degradation resulting from channel degradation due to an imbalance between sediment supply and transport capacity (Harvey and Watson, 1986; Booth, 1990). Restoration approaches may be guided by considering the relationship between bank and bed stability and may include flow peak control (watershed scale), bank stabilization, and/or grade control (Watson et al., 2002). Hard-engineering approaches to grade control have mixed success, especially in erosive, fine-bed systems (Shields, 2008). Biedenharn and Hubbard (2001) provide an overview of grade control design considerations for incised channels.

Incised channels often leave overly steepened banks which are subject to failure via mass wasting or cantilever failure (Simon et al., 2000). Hard-engineering approaches for bank stabilization, such as riprap, may be called for in certain circumstances; however, use of vegetation as a tool for restoration has gained wide acceptance with the potential to be more cost effective and longer lived [Li and Eddleman, 2002; Roni et al., 2013 (Chap. 5)]. Using natural, organic materials to construct grade control and bank stabilization structures as well as use of live stakes of woody vegetation, often referred to as bioengineering or biotechnical engineering, can achieve short-term stabilization goals and enhance in-channel and riparian habitat when the proper species and plant material are utilized [Bentrup and Hoag, 1998; Federal Interagency Stream Restoration Working Group (FISRWG), 1998 (Chap. 8)].

Alternative approaches to restoring incised channels include recruitment of beaver with the potential to create conditions for aggradation leading to wetland complexes and subsequent changes, hyporheic exchange, and habitat complexity (Naiman et al., 1988). Some concern has been voiced regarding their impedance of longitudinal connectivity for fish passage though scientific evidence largely does not support this (Lokteff et al., 2013). Pollock et al., (2014) outline a conceptual model for restoring incised channels by recruiting beaver or installing "beaver dam analogues" using anchored large wood to encourage aggradation through recruitment of other wood and sediment in a positive feedback cycle.

Rivers and Riverine Wetlands: Planform Restoration Planform restoration (rehabilitation of channel sinuosity) may be called for when restoring a formerly meandering, channelized or incised reach to reduce channel slope and encourage the habitat complexity that comes with the alternating pools, riffles, and runs associated with meandering rivers. If the physical drivers of river form are intact, planform may occur on its own so long as floodplain encroachments and/or bank armoring are removed (Kondolf, 2011). However, this scenario is rare and it is often the case that physical manipulation of the channel is required to achieve such a goal. Reach-scale restoration approaches may include filling the channelized channel and reestablishing connection with the abandoned channel (Koebel, 1995; Gore and Shields, 1995) or excavating a new, more sinuous channel over an existing incised channel (Rosgen, 1997). Caution should be taken with manipulation of river planform. The meandering river form represents a cultural archetype that may not be appropriate in all settings (Kondolf et al., 2001), and too much sinuosity can lead to under capacity and channel aggradation [Soar and Thorne, 2001 (Chap. 8)]. Soar and Thorne, 2001 (Chap. 6 and 7) present empirical relations for planform design in sand-bed rivers.

Local-Scale Hydrologic Restoration

Hydrologic restoration at the local scale of individual sites or properties in agricultural settings often involves plugging drainage ditches and canals and/or removing tile drains. Hydrologic modeling can be used to predict the effects of such activities on soil moisture regimes in order to assess the suitability of the restored site for hydrophytic plant assemblages (e.g., He et al., 2002). In urbanizing watersheds, local stormwater controls are often used at the neighborhood level to mitigate the effects of imperviousness and increased runoff on receiving waterbodies. As described earlier, hydrologic restoration through working with beaver is attracting increasing attention, and can provide a cost-effective approach to reversing the effects of channel incision (Pollock et al., 2014).

Sediment Continuity and River Restoration Design

At the stream reach scale, consideration of sediment continuity is important for channel design. This problem distills down to assuring that the reach of interest has an appropriate slope and cross-sectional dimension such that it can, over time, transport the sediment it is supplied, resulting in local sediment continuity. Sediment continuity can be evaluated at a single, design discharge (e.g., Copeland, 1994; Shields et al., 2003) or over the entire flow regime with the capacity to supply ratio [Soar and Thorne, 2001 (Chap.8), and is of most concern in labile, rivers with large sediment supplies. In coarse-bed rivers with more limited sediment supply, as evidenced by armoring, a threshold approach to channel design may be appropriate. Here, bed and bank material are sized such that they are near incipient motion at a desired flood magnitude and frequency (Wilcock, 2004). Specification of a bankfull, or design discharge, is often an important design metric; for a comprehensive review consult Soar and Thorne (2011) and Doyle et al. (2007).

136.4.5 Floodplain Restoration

Floodplain restoration may occur at multiple scales, from tens to hundreds of kilometers down to the reach scale (~ 1 km), depending on the agencies, resources, and partners involved. At large scales, it can provide for reduction in flood peaks and damage downstream, and provide rivers with room to migrate and reestablish in-channel and floodplain habitat complexity (Stammel et al., 2012; Riquier et al., 2015). Floodplain restoration may involve flow reregulation to allow for flood pulses, removing or setting back entire levee systems or allowing for controlled flood releases to access backwater areas through flood control structures for habitat and flood storage purposes (Galat et al., 1998; Hughes and Rood, 2003). At smaller scales, it may provide for local improvement in riverine habitat and some flood storage; however, it is not likely to achieve significant attenuation to flood peaks (Sholtes and Doyle, 2010). Reach-scale approaches include reestablishing hydrologic connection with side channel and floodplain habitat through physical manipulation or excavation of a floodplain bench along an incised reach [NRCS, 2007 (Chap. 10)].

Removal of post settlement alluvium is another nascent floodplain restoration approach. It involves excavating historic deposits of fine sediment accumulated behind old mill dams or leftover from hillslope erosion due to eighteenth and nineteenth century agrarian practices (Trimble, 2008; Walter and Merritts, 2008). This practice replaces incised channels eroding into post settlement alluvium, often the target of conventional restoration throughout piedmont regions of the eastern U.S. seaboard, creating wide, multithreaded channels with emergent vegetation thought to exist prior to human settlement (Hartranft et al., 2011). When practiced at the reach scale, this approach may be limited to first- and second-order channels if upstream sediment supply is large.

136.4.6 Riparian Restoration

Decades of ecological studies have documented the water quality and ecological benefits of intact buffers of riparian vegetation along streams, rivers, and wetlands, which include serving as habitat and a food source for aquatic food webs and lifecycles, shade, channel, and bank stability as well as surface and subsurface filtration of contaminated runoff (Kaushal et al., 2008; Klapproth and Johnson, 2009). Restoring riparian areas can often be cost effective as only conservation easements on buffer land are required and engineering design and earthworks are often not. Strategies for riparian restoration include cattle and game animal exclusion with fencing, planting native, ecotypic riparian woody, and herbaceous species as well as thinning mature forests to allow successional species to establish [Roni et al., 2013 (Chap. 5)]. Riparian wetlands are often impacted by construction of levee and dykes along river corridors. Removal of these constructed features along with active planting can restore these wetlands, which have an important lateral link with river ecosystems (Mitsch, 1992).

136.5 ADVANCING THE SCIENCE AND PRACTICE OF STREAM AND WETLAND RESTORATION

The practice and science of river and wetland restoration are rapidly evolving. Nevertheless, certain methodological and regulatory approaches to restoration and compensatory mitigation of impacts to streams and wetlands seem to have become entrenched and have drawn criticism. This criticism ultimately results from a lack of demonstrated restoration of ecological integrity from current practices (Bernhardt and Palmer, 2011; Doyle and Shields, 2012). Leading to this poor outcome of restoration projects are undefined or vague restoration goals (Bernhardt et al., 2005; 2007); lack of widely accepted and science-based standards for stream restoration design and practitioners (Niezgoda et al., 2014); disjoints between the scale of restoration and the scale of environmental stressors (Bernhardt and Palmer, 2011); poor or absent postrestoration monitoring programs (Bernhardt et al., 2007); and lack of published restoration results to document successes and failures (Doyle and Shields, 2012). Because restoration has become privatized in many ways (Lave et al., 2010) and treated as a commodity (acre of wetland or foot of river; Robertson, 2006) rather than an experiment (sensu; Ralph and Poole, 2002), the process of knowledge generation and application can be stymied. Wohl et al. (2005) proposed a framework for river restoration science with the goal of linking science with practice by explicitly characterizing and incorporating uncertainties, identifying effective indicators of restoration success monitoring over appropriate temporal and spatial scales, and developing and demonstrating the effectiveness of restoration methods given existing system constraints. Though more studies on the efficacy of restoration have been conducted since this framework was proposed (e.g., Alexander and Allan, 2006; Sudduth et al., 2007; Louhi et al., 2011), the science of aquatic ecosystem restoration, especially stream restoration, remains very much a work in progress.

The scientific literature and numerous case studies demonstrate the value of the following 10 principles to achieve sustainable stream and wetland restoration in a watershed context. Conversely, our many failures can commonly be traced back to ignorance of one or more of these elements (Williams et al., 1997; Frissell, 1997). We offer them as a summary of this chapter's lessons and a checklist for the restoration of streams and wetlands:

1. Address problem causes, not just symptoms; hence, focus on dynamic ecosystem processes rather than a specific, tangible form.
2. Recognize many scales, in both time and space. A long-term, large-scale, multidisciplinary perspective that includes ecological history and future changes and constraints is critical.
3. Work with, rather than against, watershed processes, and reconnect severed linkages.
4. Clearly define goals, making sure to include sustainability and enhanced ecological integrity.
5. Utilize the best available science in predictive assessments that are risk-based and decision-oriented, acknowledging the desired outcomes of primary interest to stakeholders (Dufour and Piégay, 2009), for example clean water, productive fisheries, human health and safety, recreation, and aesthetics.
6. Honestly identify and openly debate the key knowledge gaps and uncertainties, but adopt an action-oriented principle that ensures that the decision-making exercise will lead to results.
7. Make decisions in a transparent, organized framework (see Table 136.1).
8. As watershed restoration projects are as much a social undertaking as an ecological one; understand social systems and values that support and constrain restoration, while establishing long-term personal, institutional, and financial commitments.
9. Learn through careful long-term monitoring of key ecological processes and biotic elements as this enables reevaluation and updating of management strategies.
10. The best strategy is to avoid degradation in the first place. The highest emphasis should be placed on preventing further degradation, rather than on controlling or repairing damage after it has already occurred.

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REFERENCES

Alexander, G. G. and J. D. Allan, "Stream restoration in the upper Midwest, USA," *Restoration Ecology*, 14 (4): 595–604, 2006, doi:10.1111/ j.1526-100X.2006.00171.x.

Alexander, R. B., E. W. Boyer, R. A. Smith, G. E. Schwarz, and R. B. Moore, "The role of headwater streams in downstream water quality," *Journal of the American Water Resources Association*, 43 (1): 41–59, 2007, doi:10.1111/j.1752-1688.2007.00005.x.

Allan, J. D., "Landscapes and riverscapes: the influence of land use on stream ecosystems," *Annual Review of Ecology*, *Evolution, and Systematics*, 35: 257–284, 2004, doi:10.1146/annurev.ecolsys.35.120202.110122.

Allan, J. D. and M. M. Castillo, *Stream Ecology: Structure and Function of Running Waters*, 2nd ed., Springer, Secaucus, NJ, 2007, p. 445.

Baker, D. W., B. P. Bledsoe, and J. Mueller Price, Nitrate uptake and transient storage over a gradient of geomorphic complexity, north-central Colorado, USA, *Hydrological Processes*, 26 (21): 2012, 3241–3252, doi:10.1002/hyp.8385.

Bateman, H. L., D. M. Merritt, and J. B. Johnson, "Riparian forest restoration: conflicting goals, trade-offs, and measures of success," *Sustainability*, 4 (9): 2334–2347, 2012, doi:10.3390/su4092334.

Beechie, T. J., D. A. Sear, J. D. Olden, G. R. Pess, J. M. Buffington, H. Moir, and P. Roni et al., "Process-based principles for restoring river ecosystems," *BioScience*, 60 (3): 209–222, 2010, doi:10.1525/bio.2010.60.3.7.

Bentrup, G. and J. C. Hoag, *The Practical Streambank Bioengineering Guide*, Interagency Riparian/Wetland Project, U. S. Department of Agriculture—Natural Resources Conservation Service (USDA-NRCS), Plant Materials Center, Aberdeen, ID, May, 1998, p. 15, http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpu116.pdf.

Bernhardt, E. S., M. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr et al., "Synthesizing U. S. river restoration efforts," *Science*, 308 (5722), 636–637, 2005, *doi:*10.1126/science.1109769.

Bernhardt, E. S., E. B. Sudduth, M. A. Palmer, J. D. Allan, J. L. Meyer, G. Alexander, J. Follstad-Shah et al. "Restoring rivers one reach at a time: results from a survey of U.S. river restoration practitioners," *Restoration Ecology*, 15 (3): 482–493, 2007, doi:10.1111/j.1526-100X.2007.00244.x.

Bernhardt, E. S. and M. A. Palmer, "River restoration—the fuzzy logic of repairing reaches to reverse watershed scale degradation," *Ecological Applications*, 21, 1926–1931, 2011doi:10.1890/10-1574.1.

Biedenharn, D. S. and L. C. Hubbard, *Design Considerations for Siting Grade Control Structures*, Technical Note ERDC/CHL-CHETN-VII-3, U. S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS, December, 2001, p. 12.

Bledsoe, B. P. and T. H. Shear, "Vegetation along hydrologic and edaphic gradients in a North Carolina coastal plain creek bottom and implications for restoration," *Wetlands*, 20 (1), 126–147, 2000, doi:10.1672/0277-5212(2000)020[0126:VAHAEG]2.0.CO;2.

Bohn, B. A. and J. L. Kershner, "Establishing aquatic restoration priorities using a watershed approach," *Journal of Environmental Management*, 64 (4): 355–363, 2002, doi:10.1006/jema.2001.0496.

Booth, D. B., "Stream-channel incision following drainage-basin urbanization," *Journal of the American Water Resources Association*, 26 (3): 407–417, 1990, doi:10.1111/j.1752-1688.1990.tb01380.x.

Brannan, K. M., A. C. Bruggeman, T. A. Dillaha, and S. Mostaghimi, Best management practices for nonpoint source pollution control: selection and assessment, *Agricultural Nonpoint Source Pollution: Watershed Management and Hydrology*, edited by A. Shirmohammadi and W. F. Ritter, CRC Press, Danvers, MA, Chap. 10, 2001, pp. 257–304, doi:10.1201/9781420033083.ch10.

Brinson, M. M., A hydrogeomorphic classification for wetlands, *Technical Report WRP-DE-4*, Wetlands Research Program, U. S. Army Corps of Engineers Engineer, Waterways Experiment Station, Vicksburg, MS, August 1993, p. 101, doi: http://www.dtic.mil/dtic/tr/fulltext/u2/a270053.pdf.

Brown, J., "Position paper on the definition of wetland restoration. Society of Wetland Scientists (SWS)," *Wetland Science and Practice*, 17 (1): 9–10, 2000, doi:10.1672/0732-9393(2000)017[0009:PPOTDO]2.0.CO;2.

Brown, R. A. and G. B. Pasternack, "Engineered channel controls limiting spawning habitat rehabilitation success on regulated gravel-bed rivers," *Geomorphology*, 97 (3–4): 631–654, 2008, doi:10.1016/j.geomorph.2007.09.012.

Chin, A., M. D. Daniels, M. A. Urban, H. Piégay, K. J. Gregory, W. Bigler, A. Z. Butt et al., "Perceptions of wood in rivers and challenges for stream restoration in the United States," *Environmental Management*, 41 (6): 893–903, 2008, doi:10.1007/s00267-008-9075-9.

Connor, J. D., B. Franklin, A. Loch, M. Kirby, and S. A. Wheeler, "Trading water to improve environmental flow outcomes," *Water Resources Research*, 49 (7): 4265–4276, 2013, doi:10.1002/wrcr.20323.

Copeland, R. R., Application of channel stability methods—case studies, *Technical Report HL-94-11*, Flood Control Channels Research Program, U. S. Army Corps of Engineers, Waterways Experiment Station, Oxford, MS, September 1994, p. 60, http://www.dtic.mil/dtic/tr/fulltext/u2/a285625.pdf.

Doppelt, R., M. Scurlock, C. Frissell, and J. R. Karr, *Entering the Watershed: A New Approach to Save America's River Ecosystems*, Island Press, Washington, DC, 1993, p. 504.

Doyle, M. W., D. Shields, K. F. Boyd, P. B. Skidmore, and D. Dominick, "Channel-forming discharge selection in river restoration design," *Journal of Hydraulic Engineering*, 133 (7): 831–837, 2007, doi:10.1061/(ASCE)0733-9429(2007)133:7(831).

Doyle, M. W. and F. D. Shields, Jr., "Compensatory mitigation for streams under the Clean Water Act: reassessing science and redirecting policy," *Journal of the American Water Resources Association*, 48 (3): 494–509, 2012, doi:10.1111/j.1752-1688.2011.00631.x.

Dufour, S. and H. Piégay, "From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits," *River Research and Applications*, 25 (5): 568–581, 2009, doi:10.1002/rra.1239.

Einstein, H. A., Final remarks, *Sedimentation, Symposium to Honor Professor H. A. Einstein, Sedimentation Symposium*, edited by H. W. Shen,Berkeley, CA, 27–7, 1972.

Engle, R., J. Skalicky, and J. Poirier, *Translocation of Lower Columbia River Fall Chinook Salmon (Oncorhynchus tshawytscha) in the Year of Condit Dam Removal and Year One Post-removal Assessments, 2011 and 2012 Report*, U. S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA, 2013, p. 47, http://www.fws.gov/columbiariver/publications/WhiteSalmonRiverReportMarch2013.pdf.

Federal Interagency Stream Restoration Working Group (FISRWG), *Stream Corridor Restoration: Principles, Processes, and Practices*, 1998, http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1043448.

Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley, "A hierarchical framework for stream habitat classification: viewing streams in a watershed context," *Environmental Management*, 10 (2): 199–214, 1986, doi:10.1007/BF01867358.

Frissell, C. A., *Ecological principles*, *Watershed Restoration: Principles and Practices*, edited by J. E. Williams, C. A. Wood, and M. P. Dombeck, American Fisheries Society, Bethesda, MD, 1997, pp. 96–115.

Galat, D. L., L. H. Fredrickson, D. D. Humburg, K. J. Bataille, J. R. Bodie, J. Dohrenwend, G. T. Gelwicks et al., "Flooding to restore connectivity of regulated, large-river wetlands: natural and controlled flooding as complementary processes along the lower Missouri River," *BioScience*, 48 (9): 721–733, 1998, doi:10.2307/1313335.

Gordon, N. D., T. A. McMahon, B. L. Finlayson, C. J. Gippel, and R. J. Nathan, *Stream Hydrology: An Introduction for Ecologists*, 2nd ed., John Wiley & Sons, West Sussex, 2004, p. 448.

Gore, J. A. and F. D. Shields, Jr., "Can large rivers be restored?," *BioScience*, 45 (3): 142–152, 1995, doi:10.2307/1312553.

Hall, S. J., and J. B. Zedler, "Constraints on sedge meadow self-restoration in urban wetlands," *Restoration Ecology*, 18 (5): 671–680, 2010, doi:10.1111/j.1526-100X.2008.00498.x.

Hallett, L. M., S. Diver, M. V. Eitzel, J. J. Olson, B. S. Ramage, H. Sardinas, and Z. Statman-Weil et al., "Do we practice what we preach? Goal setting for ecological restoration," *Restoration Ecology*, 21 (3): 312–319, 2013, doi:10.1111/rec.12007.

Harter, P., S. Orenstein, and D. Dalton, *Better Decisions through Consultation and Collaboration*, Environmental Protection Agency, Conflict Prevention and Resolution Center, Washington, D. C., 1998, p. 136.

Hartranft, J. L., D. J. Merritts, R. C. Walter, and M. Rahnis, "The Big Spring Run experiment: policy, geomorphology, and aquatic ecosystems in the Big Spring Run watershed, Lancaster County, PA," *Sustain*, 24: 24–30, 2011, URL: https://louisville.edu/kiesd/sustain-magazine/Sustain24.pdf.

Harvey, M. D. and C. C. Watson, "Fluvial processes and morphological thresholds in incised channel restoration," *Journal of the American Water Resources Association*, 22 (3): 359–368, 1986, doi:10.1111/j.1752-1688.1986.tb01890.x.

He, X., M. J. Vepraskas, R. W. Skaggs, and D. L. Lindbo, "Adapting a drainage model to simulate water table levels in coastal plain soils," *Soil Science*

Society of America Journal, 66 (5): 1722–1731, 2002, doi:10.2136/sssaj2002.1722.

Hester, E. T. and M. N. Gooseff, "Moving beyond the banks: hyporheic restoration is fundamental to restoring ecological services and functions of streams," *Environmental Science & Technology*, 44 (5): 2010, 1521–1525, doi:10.1021/es902988n.

Hoag, J. C., S. K. Wyman, G. Bentrup, L. Holzworth, D. G. Oble, J. Carleton, and F. Berg, Users guide to description, propagation and establishment of wetland plant species and grasses for riparian areas in the intermountain west, *Technical Note Plant Materials No. 38*, U. S. Department of Agriculture—Natural Resources Conservation Service, Plant Materials Center, Aberdeen, ID, February 2001, p. 46, http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmctn380201.pdf.

Hotchkiss, R. H. and C. M. Frei, Design for fish passage at roadway-stream crossings: synthesis report, *Publication No. FHWA-HIF-07-033*, Federal Highway Administration, MacLean, VA, June 2007, p. 280, http://www.fhwa.dot.gov/engineering/hydraulics/pubs/07033/07033.pdf.

Hughes, F. M. and S. B. Rood, "Allocation of river flows for restoration of floodplain forest ecosystems: a review of approaches and their applicability in Europe," *Environmental Management*, 32 (1): 12–33, 2003, doi:10.1007/s00267-003-2834-8.

Jacobson, R. B. and J. Berkley, Conceptualizing and communicating ecological river restoration, *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches*, *Analyses and Tools*, edited by A. Simon, S. J. Bennet, and J. M. Castro, American Geophysical Union, Geophysical Monograph 194, Washington, D. C., 2011, pp. 9–27, doi:10.1029/2010GM000967.

Jaffe, M., M. Zellner, E. Minor, M. Gonzalez-Meler, L. Cotner, D. Massey, and H. Ahmed et al., *Using Green Infrastructure to Manage Urban Stormwater Quality: A Review of Selected Practices and State Programs*, Report to Illinois Environmental Protection Agency, Springfield, IL, September 2010, p. 146, https://www.uic.edu/labs/minor/GreenInfrastructureStudy.pdf.

Jensen, M. E., I. A. Goodman, C. A. Frissell, C. K. Brewer, and P. S. Bourgeron, Ecological classification and mapping of aquatic systems, *A Guidebook for Integrated Ecological Assessments*, edited by M. E. Jensen and P. S. Bourgeron, Springer-Verlag, New York, 2001, pp. 352–366.

Kail, J., D. Hering, S. Muhar, M. Gerhard, and S. Preis, "The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria," *Journal of Applied Ecology*, 44 (6): 1145–1155, 2007, doi:10.1111/j.1365-2664.2007.01401.x.

Karr, J. R., "Biological integrity: a long-neglected aspect of water resource management," *Ecological Applications*, 1 (1): 66–84, doi:10.2307/1941848.

Karr, J. R. and E. W. Chu, *Restoring Life in Running Water: Better Biological Monitoring*, Island Press, Washington, D. C., 1998, p. 220.

Kaushal, S., P. Groffman, P. Mayer, E. Striz, and A. Gold, Effects of stream restoration on denitrification at the riparian-stream interface of an urbanizing watershed of the mid-Atlantic US, *Ecological Applications*, 18 (3): 789–804, 2008.

Kayranli, B., M. Scholz, A. Mustafa, and A. Hedmark, Carbon storage and fluxes within freshwater wetlands: a critical review," *Wetlands*, 30 (1): 111–124, 2010, doi:10.1007/s13157-009-0003-4.

Keeney, R. L., "Value-focused thinking: identifying decision opportunities and creating alternatives," *European Journal of Operational Research*, 92 (3): 537–549, 1996, doi:10.1016/0377-2217(96)00004-5.

Klapproth, J. C. and J. E. Johnson, Understanding the science behind riparian forest buffers: effects on water quality, *Virginia Cooperative Extension Publication 420-151*, Virginia Tech (and Virginia State University), Blacksburg, VA, 2009, p. 21, https://pubs.ext.vt.edu/420/420-151/420-151_pdf.pdf.

Knighton, D., *Fluvial Forms and Processes: A New Perspective*, 2nd ed., Hodder Arnold, New York, 1998, p. 400.

Koebel, J. W., "An historical perspective on the Kissimmee River restoration project," *Restoration Ecology*, 3 (3): 149–159, 1995, doi:10.1111/j.1526-100X.1995.tb00167.x.

Kondolf, G. M., M. W. Smeltzer, and S. F. Railsback, "Design and performance of a channel reconstruction project in a coastal California gravel-bed stream," *Environmental Management*, 28 (6): 761–776, 2001.

Kondolf, G. M., A. J. Boulton, S. O'Daniel, G. C. Poole, F. J. Rahel, E. H. Stanley, E. Wohl et al., "Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages," *Ecology and Society*, 11 (2): 5, 2006, http://www.ecologyandsociety.org/vol11/iss2/art5/.

Kondolf, G. M., Setting goals in river restoration: when and where can the river "heal itself"?, *Stream Restoration in Dynamic Fluvial Systems*, edited by A. Simon, S. J. Bennett, and J. M. Castro, American Geophysical Union, Washington, D. C., 2011, pp. 29–43, https://institutbeaumont.files.wordpress.com/2007/09/kondolf2011-settinggoals.pdf.

LaGory, K., K. McAbee, J. Mohrman, and M. Trammell, Study plan to examine the effects of using larval razorback sucker occurrence in the Green River as a trigger for Flaming Gorge Dam peak releases, *The Upper Colorado River Endangered Fish Recovery Program*, U.S. Fish and Wildlife Service, Denver, CO, March 2012, p. 28, https://www.usbr.gov/uc/water/crsp/wg/fg/twg/pdfs/2012/larval%20trigger%20study%20plan%20-%20Final%20March%2026%202012.pdf.

Lane-Miller, C. C., S. Wheeler, H. Bjornlund, and J. Connor, "Acquiring water for the environment: lessons from natural resources management," *Journal of Environmental Policy & Planning*, 15 (4): 513–532, 2013, doi:10.1080/1523908X.2013.807210.

Lave, R., M. Doyle, and M. Robertson, "Privatizing stream restoration in the US," *Social Studies of Science*, 40 (5): 677–703, 2010, doi:10.1177/0306312710379671.

Leopold, L., M. Wolman, and J. Miller, *Fluvial Processes in Geomorphology*, W. H. Freeman, San Francisco, CA, 1964.

Li, M. H. and K. E. Eddleman, "Biotechnical engineering as an alternative to traditional engineering methods: a biotechnical streambank stabilization design approach," *Landscape and Urban Planning*, 60 (4): 225–242, 2002, doi:10.1016/S0169-2046(02)00057-9.

Lokteff, R. L., B. B. Roper, and J. M. Wheaton, "Do beaver dams impede the movement of trout?," *Transactions of the American Fisheries Society*, 142 (4): 1114–1125, 2013, doi:10.1080/00028487.2013.797497.

Louhi, P., H. Mykrä, R. Paavola, A. Huusko, T. Vehanen, A. Mäki-Petäys, and T. Muotka "Twenty years of stream restoration in Finland: little response by benthic macroinvertebrate communities," *Ecological Applications*, 21 (6): 1950–1961, doi:10.2307/41416630.

Mahoney, J. M. and S. B. Rood, "Streamflow requirements for cottonwood seedling recruitment—an integrative model," *Wetlands*, 18 (4): 634–645, 1998, doi:10.1007/BF03161678.

McKay, S. K., B. A. Pruitt, M. Harberg, A. P. Covich, M. A. Kenney, and J. C. Fischenich, *Metric Development for Environmental Benefits Analysis*, *Technical Note ERDC TN-EMRRP-EBA-11*, U. S. Army Corps of Engineers, Engineer Research and Development Center, Ecosystem Management and Restoration Research Program, Vicksburg, MS, July 2010, p. 16, http://el.erdc.usace.army.mil/elpubs/pdf/eba04.pdf.

McKay, S. K., I. Linkov, J. C. Fischenich, S. J. Miller, and L. J. Valverde, Jr., *Ecosystem Restoration Objectives and Metrics, Technical Note ERDC TN-EMRRP-EBA-16*, U. S. Army Corps of Engineers, Engineer Research and Development Center, Ecosystem Management and Restoration Research Program, Vicksburg, MS, October 2012, p. 19, http://el.erdc.usace.army.mil/elpubs/pdf/eba16.pdf.

Meade, R. H. and S. W. Trimble, Changes in sediment loads in rivers of the Atlantic drainage of the United States since 1900, *Effects of Man on the Interface of the Hydrological System with the Physical Environment*, International Association of Hydrological Sciences Publication No. 113, 1974, pp. 99–104, doi:10.1016/j.geomorph.2013.03.013.

Meitzen, K. M., M. W. Doyle, M. C. Thoms, and C. E. Burns, "Geomorphology within the interdisciplinary science of environmental flows," *Geomorphology*, 200, 143–154, 2013, doi:10.1016/j.geomorph.2013.03.013.

Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being: Wetlands and Water, Synthesis, Synthesis Reports*, World Resources Institute, Washington, D. C., 2005, p. 68, http://www.millenniumassessment.org/documents/document.358.aspx.pdf.

Mitsch, W. J., "Landscape design and the role of created, restored, and natural riparian wetlands in controlling nonpoint source pollution," *Ecological Engineering*, 1 (1–2): 27–47, 1992, doi:10.1016/0925-8574(92)90024-V.

Mitsch, W. J., X. Wu, R. W. Nairn, P. E. Weihe, N. Wang, R. Deal, and C. E. Boucher, "Creating and restoring wetlands: a whole-ecosystem experiment in self-design," *BioScience*, 48 (12): 1019–1030, 1998, doi:10.2307/1313458.

Mitsch, W. J. and S. E. Jørgensen, *Ecological Engineering and Ecosystem Restoration*, John Wiley & Sons, Hoboken, NJ, September 2003, p. 424.

Mitsch, W. J. and J. G. Gosselink, *Wetlands*, 5th ed., John Wiley & Sons, New York, 2015, p. 456.

Moore, A. A. and M. A. Palmer, "Invertebrate biodiversity in agricultural and urban headwater streams: implications for conservation and management," *Ecological Applications*, 15 (4): 1169–1177, 2005, doi:10.1890/ 04-1484.

Moreno-Mateos, D. and F. A. Comín, "Integrating objectives and scales for planning and implementing wetland restoration and creation in agricultural landscapes," *Journal of Environmental Management*, 91 (11): 2087–2095, 2010, doi:10.1016/j.jenvman.2010.06.002.

Moreno-Mateos, D., M. E. Power, F. A. Comin, and R. Yockteng, "Structural and functional loss in restored wetland ecosystems," *PLoS Biology*, 10 (1): e1001247, 2012, doi:10.1371/journal.pbio.1001247.

Mutema, M., V. Chaplot, G. Jewitt, P. Chivenge, and G. Blöschl, "Annual water, sediment, nutrient, and organic carbon fluxes in river basins: a global meta-analysis as a function of scale," *Water Resources Research*, 2015, doi:10.1002/2014WR016668.

Naiman, R. J., C. A. Johnston, and J. C. Kelley, "Alteration of North American streams by beaver," *BioScience*, 38 (11): 753–762, 1988, doi:10.2307/1310784.

Naiman, R. J., H. Décamps, and M. E. McClain, *Riparia: Ecology, Conservation, and Management of Streamside Communities*, 1st ed., Elsevier Academic, London, 2010, p. 448.

Naiman, R. J., J. R. Alldredge, D. A. Beauchamp, P. A. Bisson, J. Congleton, C. J. Henny, and N. Huntly et al., "Developing a broader scientific foundation for river restoration: Columbia River food webs," *Proceedings of the National Academy of Sciences of the United States of America*, 109 (52): 21201–21207, 2012, doi:10.1073/pnas.1213408109.

National Research Council (NRC), *Riparian Areas: Functions and Strategies for Management*, Committee on Riparian Zone Functioning and Strategies for Management, Water Science and Technology Board, NRC, National Academies Press, Washington, D. C., 2002, p. 444.

Natural Resources Conservation Service (NRCS), Wetland restoration, enhancement, or creation, *Part 650 Engineering Field Handbook*, U. S. Department of Agriculture, Natural Resources Conservation Services, Chap. 13 (210-EFH, Rev. 5/97), 1997, p. 150, http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17765.wba.

Natural Resources Conservation Service (NRCS), *Stream Restoration Design: Part 654. National Engineering Handbook*, U. S. Department of Agriculture, Natural Resources Conservation Service, Washington, D. C., August (210-VI-NEH) 2007, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/manage/restoration/?cid=stelprdb1044707.

New Jersey Department of Environmental Protection, *Regionalized Water Budget Manual for Compensatory Wetland Mitigation Sites in New Jersey*, State of New Jersey, Department of Environmental Protection, Division of Lands Use Regulation, 2008, p. 186, doi:10.7282/T36Q1X8B.

Niezgoda, S., P. Wilcock, D. Baker, J. Price, J. Castro, J. Curran, T. Wynn-Thompson et al., "Defining a stream restoration body of knowledge as a basis for national certification," *Journal of Hydraulic Engineering*, 140 (2), 123–136, 2014, doi:10.1061/(ASCE)HY.1943-7900.0000814.

Noonan, M. J., J. W. Grant, and C. D. Jackson, "A quantitative assessment of fish passage efficiency," *Fish and Fisheries*, 13 (4): 450–464, 2012, doi:10.1111/j.1467-2979.2011.00445.x.

Palmer, M. A., E. S. Bernhardt, J. D. Allan, P. S. Lake, G. Alexander, S. Brooks, J. Carr et al., "Standards for ecologically successful river restoration," *Journal of Applied Ecology*, 42 (2): 208–217, 2005, doi:10.1111/j.1365-2664.2005.01004.x.

Palmer, M. A., J. D. Allan, J. Meyer, and E. S. Bernhardt, "River restoration in the twenty-first century: data and experiential knowledge to inform future efforts," *Restoration Ecology*, 15 (3): 472–481, 2007, doi:10.1111/j.1526-100X.2007.00243.x.

Palmer, M. A., K. L. Hondula, and B. J. Koch, "Ecological restoration of streams and rivers: shifting strategies and shifting goals," *Annual Review of Ecology, Evolution, and Systematics*, 45: 247–272, 2014, doi:10.1146/annurev-ecolsys-120213-091935.

Platts, W. S. and R. L. Nelson, "Stream habitat and fisheries response to livestock grazing and instream improvement structures, Big Creek, Utah," *Journal of Soil and Water Conservation*, 40 (4): 374–379, 1985.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, and R. E. Sparks et al., "The natural flow regime," *BioScience*, 47 (11): 769–784, 1997, doi:10.2307/1313099.

Poff, N. L., B. P. Bledsoe, and C. O. Cuhaciyan, "Hydrologic variation with land use across the contiguous United States: geomorphic and ecological consequences for stream ecosystems," *Geomorphology*, 79 (3–4): 264–285, 2006, doi:10.1016/j.geomorph.2006.06.032.

Poff, N. L., B. D. Richter, A. H. Arthington, S. E. Bunn, R. J. Naiman, E. Kendy, and M. Acreman et al., "The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards," *Freshwater Biology*, 55 (1): 2010, 147–170, doi:10.1111/j.1365-2427.2009.02204.x.

Pollock, M. M., T. J. Beechie, J. M. Wheaton, C. E. Jordan, N. Bouwes, N. Weber, and C. Volk, "Using beaver dams to restore incised stream ecosystems," *BioScience*, 64 (4): 279–290, 2014, doi:10.1093/biosci/biu036.

Ralph, S. C. and G. C. Poole, Putting monitoring first: designing accountable ecosystem restoration and management plans, *Restoration of Puget Sound Rivers*, edited by D. R. Montgomery, S. Bolton, D. B. Booth, L. Wall, and D. B. Booth, University of Washington Press, Seattle, WA, Chap. 9, 2002, pp. 222–242, 512.

Reid, L. M. and T. Dunne, *Rapid Evaluation of Sediment Budgets*, *GeoEcology Texts*, Catena Verlag GMBH, Reiskirchen, 1996, p. 164.

Richardson, M. S., and R. C. Gatti, "Prioritizing wetland restoration activity within a Wisconsin watershed using GIS modeling," *Journal of Soil and Water Conservation*, 54 (3): 537–542, 1999.

Riquier, J., H. Piégay, and M. Šulc Michalková, "Hydromorphological conditions in eighteen restored floodplain channels of a large river: linking patterns to processes," *Freshwater Biology*, 60 (6): 1085–1103, 2015, doi:10.1111/fwb.12411.

Robertson, M. M., "The nature that capital can see: science, state, and market in the commodification of ecosystem services," *Environment and Planning D*, 24 (3): 367–387, 2006, doi:10.1068/d3304.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess, A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds, *North American Journal of Fisheries Management*, 22 (1): 2002, doi:10.1577/1548-8675(2002)022<0001:AROSRT>2.0.CO;2.

Roni, P. and T. Beechie, *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats*, Wiley-Blackwell, December 2012, p. 316.

Roni, P., G. Pess, K. Hanson, and M. Pearsons, Selecting appropriate stream and watershed restoration techniques, *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats*, Chap. 5, edited by, P. Roni and T. Beechie, Wiley-Blackwell, Hobokon, NJ, 2013, pp. 144–188.

Rosgen, D. L., A geomorphological approach to restoration of incised rivers, *Management of Landscapes Disturbed by Channel Incision*, *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, edited by S. Y. Wang, E. J. Langendoen, and F. D. Shields, Jr., University of Mississippi, Center for Computational Hydroscience and Engineering, Oxford, MS, May 19–23, 1997, p. 11.

Rosgen, D. L., *Watershed Assessment of River Stability and Sediment Supply (WARSSS)*, 1st ed., Wildland Hydrology, Fort Collins, CO, 2007, p. 193.

Sanderson, J. S., N. Rowan, T. Wilding, B. P. Bledsoe, W. J. Miller, and N. L. Poff, "Getting to scale with environmental flow assessment: the watershed flow evaluation tool," *River Research and Applications*, 28 (9): 1369–1377, 2012, doi:10.1002/rra.1542.

Schkade, D. A., T. D. Feather, and D. T. Capan, Environmental evaluation: the role of stakeholder communication and collaborative planning, *IWR Report 96-R-17*, U.S. Army Corps of Engineers, Institute for Water Resources, Alexandra, VA, June p. 66, 1996.

Schmidt, J. C. and P. R. Wilcock, "Metrics for assessing the downstream effects of dams," *Water Resources Research*, 44 (4): 2008, doi:10.1029/2006WR005092.

Schumm, S. A., M. D. Harvey, and C. C. Watson, *Incised Channels: Morphology, Dynamics, and Control*, Water Resources Publications, Littleton, CO, 1984, p. 208.

Shields, Jr., F. D., R. Copeland, P. Klingeman, M. Doyle, and A. Simon, "Design for stream restoration," *Journal of Hydraulic Engineering*, 129 (8): 575–584, doi:10.1061/(ASCE)0733-9429(2003)129:8(575).

Shields, Jr., F. D., N. Morin, and C. M. Cooper, "Large woody debris structures for sand-bed channels," *Journal of Hydraulic Engineering*, 130 (3): 208–217, doi:10.1061/(ASCE)0733-9429(2004)130:3(208).

Shields, Jr., F. D., "Long-term evaluation of regional erosion control," *Journal of Soil and Water Conservation*, 63 (2): 50A, doi:10.2489/jswc.63.2.50A.

Sholtes, J. S. and M. W. Doyle, "Effect of channel restoration on flood wave attenuation," *Journal of Hydraulic Engineering*, 137 (2): 196–208, 2010, doi:10.1061/(ASCE)HY.1943-7900.0000294.

Simon, A., A. Curini, S. E. Darby, and E. J. Langendoen, "Bank and near-bank processes in an incised channel," *Geomorphology*, 35 (3–4): 193–217, 2000, doi:10.1016/S0169-555X(00)00036-2.

Skidmore, P. B., C. R. Thorne, B. L. Cluer, G. R. Pess, J. M. Castro, T. J. Beechie, and C. C. Shea, *Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals, NOAA Technical Memorandum NMFS-NWFSC-112*, NMFS-NWFSC Series, U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Northwest Fisheries Science Center (NWFSC), Seattle, WA, October 2011, p. 255, http://www.restorationreview.com/downloads/Science_and_Tools_for_Stream_Projects_2011.pdf.

Smith, S. M. C., P. Belmont, and P. R. Wilcock, Closing the gap between sediment budgeting and stream restoration planning, *Stream Restoration in Dynamic Systems: Scientific Approaches, Analyses, and Tools: Geophysical Monograph Series, Geophysical Monograph 194*, edited by A. Simon, S. J. Bennett, and J. M. Castro, American Geophysical Union, Washington, D. C., 2011, pp. 293–317, doi:10.1029/2011GM001085.

Soar, P. J. and C. R. Thorne, Channel restoration design for meandering rivers, *ERDC/CHL CR-01-1*, U. S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Flood Damage Reduction Research Program, Vicksburg, MS, September 2001, p. 437, http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.

Soar, P. J. and C. R. Thorne, Design discharge for river restoration, *Stream Restoration in Dynamic Fluvial Systems: American Geophysical Union, Geophysical Monograph Series, Geophysical Monograph 194*, edited by A. Simon, S. J. Bennett, and J. M. Castro, Washington, D. C., 2011, pp. 123–149, doi:10.1029/GM194.

Society for Ecological Restoration (SER) International Science & Policy Working Group, *The SER International Primer on Ecological Restoration*, Version 2, October 2004, p. 16, http://www.ser.org/docs/default-document-library/ser_primer.pdf?sfvrsn=2.

Southwood, T. R. E., "Habitat, the template for ecological strategies?," *The Journal of Animal Ecology*, 46: 337–365, 1977, http://www.britishecologicalsociety.org/100papers/100_Ecological_Papers/100_Influential_Papers_072.pdf.

Stammel, B., B. Cyffka, J. Geist, M. Müller, J. Pander, G. Blasch, P. Fischer et al., "Floodplain restoration on the Upper Danube (Germany) by re-establishing water and sediment dynamics: a scientific monitoring as part of the implementation," *River Systems*, 20 (1–2): 55–70, 2012, doi:10.1127/1868-5749/ 2011/020-0033.

Sudduth, E. B., J. L. Meyer, and E. S. Bernhardt, "Stream restoration practices in the southeastern United States," *Restoration Ecology*, 15 (3): 573–583, 2007, doi:10.1111/j.1526-100X.2007.00252.x.

Sudduth, E. B., B. A. Hassett, P. Cada, and E. S. Bernhardt, "Testing the field of dreams hypothesis: functional responses to urbanization and restoration in stream ecosystems," *Ecological Applications*, 21 (6): 1972–1988, 2011.

Suding, K. N., K. L. Gross, and G. R. Houseman, "Alternative states and positive feedbacks in restoration ecology," *Trends in Ecology & Evolution*, 19 (1): 46–53, 2004, doi:10.1016/j.tree.2003.10.005.

Suedel, B. C., K. Burks-Copes, J. Kim, and S. K. McKay, Using multi-criteria decision analysis to support ecosystem restoration planning, *Technical Note ERDC TN-EMRRP-EBA-7*, U. S. Army Corps of Engineers, Engineer Research and Development Center, Ecosystem Management and Restoration Research Program, Vicksburg, MS, March 2011, p. 17, http://el.erdc.usace.army.mil/elpubs/pdf/eba07.pdf.

Tal, M., K. Gran, A. B. Murray, C. Paola, and D. M. Hicks, Riparian vegetation as a primary control on channel characteristics in multi-thread rivers, *Riparian Vegetation and Fluvial Geomorphology: Hydraulic, Hydrologic, and Geotechnical Interaction*, edited by S. J. Bennett and A. Simon, American Geophysical Union, Washington, D. C., 2004, pp. 43–58.

Trimble, S. W., *Man-Induced Soil Erosion on the Southern Piedmont: 1700-1970*, Enhanced 2nd ed., Soil and Water Conservation Society, Ankeny, IA, 2008, p. 80.

U. S. Forest Service (USFS), *Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-stream Crossings*, U. S. Department of Agriculture, National Technology and Development Program, Forest Service Stream-simulation Working Group, San Dimas Technology and Development Center (SDTDC 0877 1801), San Dimas, CA, May 2008, http://www.fs.fed.us/eng/pubs/pdf/StreamSimulation/.

Verhoeven, J. T. A., "Wetlands in Europe: perspectives for restoration of a lost paradise," *Ecological Engineering*, 66: 6–9, 2014, doi:10.1016/j.ecoleng.2013.03.006.

Viparelli, E., D. Gaeuman, P. Wilcock, and G. Parker, "A model to predict the evolution of a gravel bed river under an imposed cyclic hydrograph and its application to the Trinity River," *Water Resources Research*, 47 (2): 2011, doi:10.1029/2010WR009164.

Vivian, L. M., D. J. Marshall, and R. C. Godfree, "Response of an invasive native wetland plant to environmental flows: implications for managing regulated floodplain ecosystems," *Journal of Environmental Management*, 132, 268–277, doi:10.1016/j.jenvman.2013.11.015.

Walter, R. C. and D. J. Merritts, "Natural streams and the legacy of water-powered mills," *Science*, 319 (5861): 299–304, 2008, doi:10.1126/science.1151716.

Ward, J. V., "The four-dimensional nature of lotic ecosystems," *Journal of the North American Benthological Society*, 8 (1): 2–8, 1989, http://www.jstor.org/stable/1467397.

Watson, C. C., D. S. Biedenharn, and B. P. Bledsoe, "Use of incised channel evolution models in understanding rehabilitation alternatives," *Journal of the American Water Resources Association*, 38 (1): 151–160, 2002, doi:10.1111/j.1752-1688.2002.tb01542.x.

White, D. and S. Fennessy, "Modeling the suitability of wetland restoration potential at the watershed scale," *Ecological Engineering*, 24 (4): 359–377, 2005, doi:10.1016/j.ecoleng.2005.01.012.

White, S. L., C. Gowan, K. D. Fausch, J. G. Harris, and W. C. Saunders, "Response of trout populations in five Colorado streams two decades after habitat manipulation," *Canadian Journal of Fisheries and Aquatic Sciences*, 68 (12): 2057–2063, 2011, doi:10.1139/f2011-125.

Whiting, P. J., "Streamflow necessary for environmental maintenance," *Annual Review of Earth and Planetary Sciences*, 30 (1): 181–206, 2002.

Wilcock, P. R., Sediment transport in the restoration of gravel-bed rivers, *Proceedings of the ASCE 2004 Environmental and Water Resources Annual Congress*, edited by G. Sehlke, D. F. Hayes, and D. K. Stevens, Salt Lake City, UT, June 27–July 1, 2004, pp. 1–11.

Wilcock, P., J. Pitlick, and Y. Cui, *Sediment Transport Primer: Estimating Bed-Material Transport in Gravel-bed Rivers*, General Technical Report RMRS-GTR-226, U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, May 2009, p. 78, http://www.fs.fed.us/rm/pubs/rmrs_gtr226.pdf.

Williams, J. E., C. A. Wood, and M. P. Dombeck, *Watershed Restoration: Principles and Practices*, American Fisheries Society, Bethesda, MD, 1997, p. 549.

Williams, J. E., C. A. Wood, and M. P. Dombeck, Understanding watershed-scale restoration, *Watershed Restoration: Principles and Practices*, edited by J. E. Williams, C. A. Wood, and M. P. Dombeck, American Fisheries Society, Bethesda, MD, 1997, pp. 1–16.

Williams, K. B., *The Potential Wetland Restoration and Enhancement Site Identification Procedure: A Geographic Information System for Targeting Wetland Restoration and Enhancement*, North Carolina Division of Coastal Management, Department of Environment and Natural Resources, The Coastal Zone Enhancement Grants Program, December, 2002, p. 39.

Wissmar, R. C. and P. A. Bisson, *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, American Fisheries Society, Bethesda, MD, 2003, p. 276.

Wohl, E., P. L. Angermeier, B. Bledsoe, G. M. Kondolf, L. MacDonnell, D. M. Merritt, M. A. Palmer et al., "River restoration," *Water Resources Research*, 41 (10), W10301, 2005, doi:10.1029/2005WR003985.

Wohl, E., Seeing the forest and the trees: wood in stream restoration in the Colorado Front Range, United States, *Stream Restoration in Dynamic Fluvial Systems*, edited by A. Simon, S. J. Bennett, and J. M. Castro, American Geophysical Union, Washington, D. C., 2011, p. 544.

Wohl, E., *Rivers in the Landscape: Science and Management*, John Wiley & Son, West Sussex, 2014, p. 318.

Wohl, E., B. P. Bledsoe, R. B. Jacobson, N. L. Poff, S. L. Rathburn, D. M. Walters, and A. C. Wilcox, "The natural sediment regime in rivers: broadening the foundation for ecosystem management," *BioScience*, 5 (4): 358–371, 2015, doi:10.1093/biosci/biv002.

Wunderlich, R. C., B. D. Winter, and J. H. Meyer, "Restoration of the Elwha River ecosystem," *Fisheries*, 19 (8): 11–19, 1994.

Zedler, J. B., "Progress in wetland restoration ecology," *Trends in Ecology & Evolution*, 15 (10): 402–407, doi:10.1016/S0169-5347(00)01959-5.