

River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation

EMILY S. BERNHARDT^{1,4} AND MARGARET A. PALMER^{2,3}

¹*Department of Biology, Duke University, Durham, North Carolina 27708 USA*

²*University of Maryland Center for Environmental Science, Solomons, Maryland 20688 USA*

³*Department of Entomology, University of Maryland, College Park, Maryland 20742 USA*

Abstract. River restoration is an increasingly common approach utilized to reverse past degradation of freshwater ecosystems and to mitigate the anticipated damage to freshwaters from future development and resource-extraction activities. While the practice of river restoration has grown exponentially over the last several decades, there has been little empirical evaluation of whether restoration projects individually or cumulatively achieve the legally mandated goals of improving the structure and function of streams and rivers. New efforts to evaluate river restoration projects that use channel reconfiguration as a methodology for improving stream ecosystem structure and function are finding little evidence for measurable ecological improvement. While designed channels may have less-incised banks and greater sinuosity than the degraded streams they replace, these reach-scale efforts do not appear to be effectively mitigating the physical, hydrological, or chemical alterations that are responsible for the loss of sensitive taxa and the declines in water quality that typically motivate restoration efforts. Here we briefly summarize this new literature, including the collection of papers within this Invited Feature, and provide our perspective on the limitations of current restoration.

Key words: catchment land use; evaluation; natural channel design; river restoration; streams; water quality.

INTRODUCTION

The water quality and biodiversity of freshwaters are declining globally. While high-profile examples like the historic “flaming Cuyahoga River of Ohio” or the desperately polluted Ganges may grab the headlines, the bulk of the damage to our global rivers falls into two categories: degradation resulting from major alterations to the landscape or from excessive water withdrawals and construction of dams (Nilsson et al. 2005, Dudgeon et al. 2006). While both types of degradation occur worldwide, the former is a common motivation for river restoration in wet climates such as in the eastern United States and much of Europe where high flows and polluted runoff may accompany land use change. The latter drives restoration efforts particularly in arid or semiarid climates including much of the western United States, the Middle East, Australia, and parts of Africa. Just as the source of degradation differs between these two types, so too do the restoration approaches.

Efforts to restore biodiversity and ecological function in rivers that have been dammed or subjected to flow diversions have included reestablishing part of the historic flow regime, removing levees to recover floodplain functionality, scheduling water releases from reservoirs to restore native vegetation and riparian functions, and in some cases even removing flow blockages or reconnecting river reaches that have been fragmented (Bednarek 2001, Stromberg 2001, Doyle et al. 2005, Richter and Thomas 2007). While reducing diversions and removing dams have not uniformly been successful in restoring native flora and fauna, there are certainly success stories (e.g., Rood et al. 2003, Hall et al. 2010). Many of these involved restoring flows to river reaches that were “water starved” or had blockages that significantly limited upstream fish dispersal (Rood et al. 2005, Catalano et al. 2007) but were otherwise not seriously stressed by other factors such as uncontrolled runoff or non-point-source pollution.

Efforts to restore biodiversity and ecological function in streams and rivers degraded by substantial land use change or by human activities such as agriculture, development, and channelization have proved to be much more difficult, and reports of effectiveness monitoring (pre- and post-restoration quantitative sampling) of restoration outcome are rare (Bernhardt et al. 2005, Palmer et al. 2005). Yet, human activities

Manuscript received 9 August 2010; revised 2 December 2010; accepted 3 December 2010; final version received 31 January 2011. Corresponding Editor: C. Nilsson. For reprints of this Invited Feature, see footnote 1, p. 1925.

⁴ E-mail: emily.bernhardt@duke.edu

leading to non-point-source pollution and channel degradation are among the most common motivations for undertaking stream restoration (Walsh et al. 2005, Bernhardt and Palmer 2007) often involving significant channel reconfiguration efforts. Typically these restoration projects focus on increasing channel stability and in-stream habitat by altering channel form and structure along a river reach (Niezgoda and Johnson 2005) with the hopes of restoring stream ecosystems (Rosgen 1996, Hey 2006). These channel-based or “hydromorphological” restoration projects are extremely common worldwide (e.g., Jähnig et al. 2009), and new research efforts to evaluate their ecological effectiveness are just beginning to be published (e.g., Tullos et al. 2009, Baldigo et al. 2010, Miller and Kochel 2010, Miller et al. 2010).

This Invited Feature presents a series of papers that evaluate the ecological outcomes of channel reconfiguration restoration projects in the eastern United States and western Europe. To provide background and context, we first provide a very brief summary of recent publications that have reviewed the scientific basis or ecological outcomes of multiple river restoration projects. The types of projects discussed in these publications are diverse, but we focus primarily on publications that have evaluated channel reconfiguration projects. Overviews of projects directed at restoring environmental flows or riparian zones are available elsewhere (e.g., see special journal issues associated with Arthington et al. [2010] and Mayer et al. [2010]).

Background

The literature on restoration effectiveness is growing. Several recent papers have attempted to synthesize reports of restoration evaluations (Roni et al. 2008, Miller and Kochel 2010, Miller et al. 2010, Palmer et al. 2010, Whiteway et al. 2010). After reviewing a wide variety of stream restoration projects (345 studies), Roni et al. (2008) concluded that few firm conclusions could be reached “because of the limited information provided on physical habitat, water quality, and biota and because of the short duration and limited scope of most published evaluations.” Whiteway et al. (2010) offer a more optimistic perspective, finding that, of 211 river restoration projects aimed at restoring salmonid fish, the majority of projects led to an increase in the abundance or biomass of fish although, we note, that most projects do not distinguish aggregation effects from population-level increases. Baldigo et al. (2010) used a thorough before–after–control–impact (BACI) assessment design and found that in four of six “natural channel design” projects, increases in salmonid biomass were also accompanied by small increases in young-of-the-year trout, suggesting the potential for population-level effects. Because such changes were negligible or absent in two of the projects they studied, Baldigo et al. (2010) emphasize that positive ecological responses from channel design projects should not be presumed and that increases in channel stability do not necessarily lead

to improved fish habitat. It is important to recognize that most projects analyzed in these syntheses were less than a decade post-construction. The lack of demonstrable ecological improvements may thus be due either to a lack of effective physical, chemical, or hydrologic remediation or merely to a lack of time for recovery. Even if restoration efforts could be reliably expected to generate ecological improvements within subsequent decades, such time lags between implementation and ecological recovery must temper expectations that restoration efforts can effectively and quickly mitigate river degradation elsewhere.

Many evaluations of stream restoration projects rely on diversity and species composition of macroinvertebrates as an indicator of ecological outcome and while a growing number of publications report on the outcome of one or a few projects (e.g., Yu et al. 2010), there are also some recent syntheses. Palmer et al. (2010) found that, of 78 channel restoration projects, only two documented a significant improvement in macroinvertebrate species richness or compositional shift toward reference conditions. While they did not measure invertebrate response, the work by Miller and Kochel (2010) was sufficiently comprehensive (monitored 26 restoration projects), that it is worth noting here. Their geomorphic monitoring programs led them to conclude that attempts to restore rivers through channel reconfiguration are extremely difficult because they can lead to major channel adjustments and failures of in-stream structures: “there is little evidence from the examined projects in North Carolina that reconfiguring straightened and/or incised channels along highly dynamic rivers will speed the rate of recovery” (Miller and Kochel 2010:1690).

Contributing papers

Unfortunately, the conclusions of papers comprising this Invited Feature are sobering. Empirical evaluation of a variety of channel-based restoration projects documented little evidence of ecologically successful outcomes. Violin et al. (2011) found that urban stream restoration efforts in the southeastern United States had no demonstrable effect on habitat diversity or on macroinvertebrate communities. More disheartening, several restored streams in Finland were found to have stream invertebrate communities that were depauperate relative to unrestored upstream reference reaches even 15 years following restoration (Louhi et al. 2011). Restored urban streams in North Carolina were found to have significantly higher temperatures than unrestored urban streams as a result of removing riparian trees to facilitate restoration projects (Sudduth et al. 2011). Filoso and Palmer (2011) show that efforts to reduce the flux of nitrogen to coastal waters through hydrogeomorphic stream restoration approaches are rarely successful. Instead, N-removal capacity may depend more on N concentrations than restoration treatment, and projects are unlikely to provide signifi-

cant N-reducing benefits unless the “restoration” project involved converting the stream to a very different type of ecosystem such as a wetland–stream complex (i.e., the end result is a system that may not even have the ecological characteristics of a stream anymore). Despite a lack of measurable ecological improvement (*sensu* Palmer et al. 2005), most restoration practitioners consider their projects to be successful (Bernhardt et al. 2007, Jähnig et al. 2011).

ADAPTIVE RESTORATION

With a rapidly expanding body of literature evaluating river restoration effectiveness, we can move from asking “Why don’t we know more about river restoration success?” (Bernhardt et al. 2005, Palmer et al. 2005) to asking “Why aren’t river restoration projects more effective?” We offer some thoughts that were in part informed by the papers in this Invited Feature, but we want to emphasize the value of past monitoring efforts. The published assessments of restored streams and river reaches have provided a great deal of information that can inform future project designs. Documented failures with good data are fodder for understanding what went wrong and why—indeed, as we emphasized in Palmer et al. (2005), learning from past efforts can be considered one of at least three forms of restoration success (i.e., in addition to ecological improvements and meeting stakeholder needs). As countries around the world move forward in developing restoration plans, we suggest that future projects should be informed by results from past efforts and ecological theory (O’Donnell and Galat 2007, Woolsey et al. 2007). In calling for “restoration reform,” Palmer (2009) discusses in depth factors that should drive river future restoration efforts, and Beechie et al. (2010) provide insightful perspectives on moving toward more process-based restoration. Here we mention four of those factors and perspectives that papers in this Invited Feature help illuminate.

First, much more emphasis needs to be placed on site selection for restoration projects: spatial context may be one of the most important factors controlling stream restoration outcome. Sundermann et al. (2011) found that most of the restored streams they sampled in Germany showed no measurable improvement in macroinvertebrate communities; the few that did were close to intact, forested catchments. They suggest that the proximity of a restored stream reach to potential sources of colonists is an important determinant of restoration success, or, in other words, that the provision of habitat is insufficient if target taxa must disperse long distances within degraded channels or across altered landscapes to colonize a restored site. Another interpretation of these same data might be that river reaches in catchments with less total disturbance have a higher potential to recover from targeted efforts. Additionally, Filoso and Palmer (2011) show that position within a catchment (upland vs. lowland restoration project) may have a major impact on the

nitrogen removal capacity of restored Coastal Plain reaches in urban areas. They found that, during high flows when most of the N is exported, lowland reaches with gentle slopes and wider valleys have higher hydraulic retention and, therefore, capacity to retain N.

Second, given that a number of studies have now found no ecological improvement from channel reconfiguration projects and, in some cases, even found evidence of increased degradation (e.g., Tullos et al. 2009), future restoration approaches should keep earth-moving activities to a minimum, particularly if they include the removal of trees. The studies by Louhi et al. (2011) and Sudduth et al. (2011) both present evidence that restoration activities themselves actually lead to degradation that is not necessarily short lived. In a series of timber-floated streams in Finland, Louhi et al. (2011) found that a critical habitat, native bryophyte patches, did not recover, and thus limited the recovery of stream invertebrates that typically inhabit these patches. Potential colonists were present above the restored reaches, and thus this was not a case of dispersal limitation. Sudduth et al. (2011) document a very different type of habitat degradation post-restoration. They show that the urban streams they studied were significantly warmer with more sunlight penetrating the water post-restoration. The most extensive and expensive types of restoration projects (natural channel design, floodplain reconnection) require, at a minimum, significant earth-moving and temporary piping or rerouting of stream flow. Empirical evaluation of 24 restoration sites led Tullos et al. (2009) to conclude that channel reconfiguration acts as a “disturbance filter” such that taxa sensitive to disturbance were characteristic of their control reaches, whereas insensitive taxa were characteristic of restored reaches. They attributed this to the disturbance effect on food resources and channel stability. Acknowledging that this could be a temporary impact (Tullos et al. [2009] projects were 1–4 years old), the results of Sudduth et al. (2011; projects 1–6 years old), Louhi et al. (2011; some projects 12 years old), and Palmer et al. (2010; some projects 16 years old) suggest that the unintended consequences of restoration may persist for some time.

Third, restoration of streams and rivers should not be expected to alleviate problems generated throughout a catchment. The very problems that lead to stream degradation typically are catchment-scale problems (e.g., large amounts of impervious cover or land in agriculture). Projects that are small in scope simply cannot handle the level of impacts, and yet the vast majority of restoration projects are small and isolated. Even for projects that are large, streams simply cannot always “repair” problems created at broad scales. For example, Filoso and Palmer (2011) found that, across the restored sites they studied, nitrogen (N) export to downstream waters was reduced in restored reaches by a maximum of 11% during base-flow conditions, and 24% during high flows. However, this amounted to only ~5%

of the total N input into the catchment. Further, these “high” N removal values are for a stream that was converted to a stream–wetland complex. Some of the more traditionally restored stream reaches actually contributed more N to downstream waters than control reaches. As we have previously argued, these results highlight the need to reduce N sources on the land and improve land-based “best management practices” (BMPs; Bernhardt and Palmer 2007, Bernhardt et al. 2008).

Fourth, future efforts must shift from a focus on geomorphic structure and form to a focus on restoration of the hydrologic, geomorphic, and biological processes that maintain healthy stream ecosystems. There is a widespread practice of applying structural approaches to restore ecological communities rather than process-based approaches (Roni et al. 2002, 2008), and one of the most widely applied and controversial restoration approaches, natural channel design, focuses exclusively on matching the pattern, profile, and dimension of stream channels to pre-degradation or reference conditions (Rosgen 1994, Lave 2009). There are a few types of restoration activities that are explicitly designed to restore river processes. Most notably the dam and levee removal projects we mentioned at the outset of our article are designed to reinstate disrupted hydrological and sediment-flux processes along river networks or between rivers and their floodplains (Bednarek 2001, Hart et al. 2002, Stanley and Doyle 2003). Although not currently classified as river restoration, efforts to retain and detain storm waters in urban or agricultural catchments can similarly help restore a more natural flow regime. A variety of catchment BMPs and infrastructure improvements aimed at reducing contaminant loading to streams can also “restore” more natural chemical fluxes to degraded stream ecosystems. The current overemphasis on structural improvements to channels in restoration is likely a result of river restoration approaches emerging out of classic hydraulic engineering (see discussion in Lave [2009]).

CONCLUSIONS AND SOCIAL CONTEXT

In the same way that national and international plans for adaptive fisheries management have been difficult to implement (Francis et al. 2007, Walters 2007), adaptive restoration that allows for changes in the design and conceptualization of river and catchment projects will be very difficult to implement. Just as scientists are hesitant to break free of accepted theories, practitioners and managers are hesitant to experiment with new approaches. Additionally, regulatory agencies often incorporate restoration method requirements into policy instruments (Lave 2009), and changes to such policies often lag a decade or more behind the science. Efforts to streamline the regulatory process can also severely constrain opportunities for developing, implementing, and testing innovative approaches to improving the conditions of degraded streams. For example, require-

ments that stream restoration be “in kind” currently prevent catchment managers from spending restoration dollars for out-of-channel improvements in water management that might ultimately better protect water and habitat quality. If regulatory agencies insisted upon evidence of desirable outcomes (e.g., improved water quality, restored environmental flows or dampened floods, improvements in the diversity or abundance of target taxa) rather than requiring particular approaches or evidence of structural changes to the channel, this would provide opportunities for experimentation and the development of a broader array of tools and approaches for reversing and preventing degradation of river ecosystems.

We are optimistic that the recent spate of publications on restoration outcomes is making a difference. Both of us are aware of new efforts in the United States, Europe, and Australia to prioritize and plan restoration efforts at catchment scales, and we believe this reflects not only new scientific findings, but perhaps more importantly an increase in social pressure and environmental awareness. Streams and rivers reflect what we do on the land, and rather than working at the end of the pipe (the stream), community groups and managers may need to be focusing their energies on protecting streams and rivers from continued degradation by keeping storm waters, nutrients, and contaminants contained within catchments. Recognizing the extreme fragility of healthy streams and the nearly insurmountable challenges to stream restoration in the catchments where most people live and work must give us pause—and force us to raise the bar when deciding whether to fill, pipe, or otherwise further degrade stream ecosystems. Finally, we have to recognize that, in many catchments, river restoration (i.e., channel projects) will never be “good enough.” In highly altered agricultural, urban, and suburban landscapes, elevated supplies of storm waters, nutrients, and contaminants to stream ecosystems impose serious constraints on what can be achieved both structurally and functionally through stream engineering. Instead, effective “restoration” in catchments with agricultural or urban development must first focus on slowing and interrupting the heightened hydrologic connectivity between heavily altered catchments and draining streams, thereby improving water quality and reducing peak flows. Protecting and promoting healthy riparian vegetation and reinstating the reduced hydrologic connectivity between streams and their floodplains are important and necessary next steps. Such measures may be sufficient to promote biological recovery in impacted streams; however, structural enhancements within the stream channel will likely be necessary to create and reinstate appropriate habitat diversity.

ACKNOWLEDGMENTS

The authors thank Dave Strayer and an anonymous reviewer for their constructive review and improvement of this article. The authors also thank Christy Violin and Elizabeth Sudduth for comments on an earlier version of the manuscript.

LITERATURE CITED

- Arthington, A. H., R. J. Naiman, M. E. McClain, and C. Nilsson. 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology* 55:1–16.
- Baldigo, B. P., A. G. Ernst, D. R. Warren, and S. J. Miller. 2010. Variable responses of fish assemblages, habitat, and stability to natural-channel-design restoration in Catskill Mountain streams. *Transactions of the American Fisheries Society* 139:449–467.
- Bednarek, A. T. 2001. Undamming rivers: a review of the ecological impacts of dam removal. *Environmental Management* 27:803–814.
- Beechie, T. J., D. A. Sear, J. D. Olden, G. R. Pess, J. M. Buffington, H. Moir, P. Roni, and M. M. Pollock. 2010. Process-based principles for restoring river ecosystems. *BioScience* 60:209–222.
- Bernhardt, E. S., L. E. Band, C. J. Walsh, and P. E. Berke. 2008. Understanding, managing, and minimizing urban impacts on surface water nitrogen loading. *Annals of the New York Academy of Sciences* 1134:61–96.
- Bernhardt, E. S., et al. 2005. Can't see the forest for the stream? In-stream processing and terrestrial nitrogen exports. *BioScience* 55:219–230.
- Bernhardt, E. S., and M. A. Palmer. 2007. Restoring streams in an urbanizing world. *Freshwater Biology* 52:738–751.
- Bernhardt, E. S., E. B. Sudduth, M. A. Palmer, J. D. Allan, J. L. Meyer, G. Alexander, J. Follstad-Shah, B. Hassett, R. Jenkinson, R. Lave, J. Rumps, and L. Pagano. 2007. Restoring rivers one reach at a time: results from a survey of US river restoration practitioners. *Restoration Ecology* 15:482–493.
- Catalano, M. J., M. A. Bozek, and T. D. Pellett. 2007. Effects of dam removal on fish assemblage structure and spatial distributions in the Baraboo River, Wisconsin. *North American Journal of Fisheries Management* 27:519–530.
- Doyle, M. W., E. H. Stanley, D. L. Strayer, R. B. Jacobson, and J. C. Schmidt. 2005. Effective discharge analysis of ecological processes in streams. *Water Resources Research* 41:W11411.
- Dudgeon, D., A. H. Arthington, M. O. Gessner, Z. I. Kawabata, D. J. Knowler, C. Leveque, R. J. Naiman, A. H. Prieur-Richard, D. Soto, M. L. J. Stiassny, and C. A. Sullivan. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* 81:163–182.
- Filoso, S., and M. Palmer. 2011. Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters. *Ecological Applications* 21:1989–2006.
- Francis, R. C., M. A. Hixon, M. E. Clarke, S. A. Murawski, and S. Ralston. 2007. Fisheries management: ten commandments for ecosystem-based fisheries scientists. *Fisheries* 32:217–233.
- Hall, A. A., S. B. Rood, and P. S. Higgins. 2010. Resizing a river: a downscaled, seasonal flow regime promotes riparian restoration. *Restoration Ecology*. [doi: 10.1111/j.1526-100X.2009.00581.x]
- Hart, D. D., T. E. Johnson, K. L. Bushaw-Newton, R. J. Horwitz, A. T. Bednarek, D. F. Charles, D. A. Kreeger, and D. J. Velinsky. 2002. Dam removal: challenges and opportunities for ecological research and river restoration. *BioScience* 52:669–681.
- Hey, R. D. 2006. Fluvial geomorphological methodology for natural stable channel design. *Journal of the American Water Resources Association* 42:357–374.
- Jähnig, S. C., A. W. Lorenz, and D. Hering. 2009. Restoration effort, habitat mosaics, and macroinvertebrates—does channel form determine community composition? *Aquatic Conservation: Marine and Freshwater Ecosystems* 19:457–169.
- Jähnig, S. C., A. W. Lorenz, D. Hering, C. Antons, A. Sundermann, E. Jedicke, and P. Haase. 2011. River restoration success: a question of perception. *Ecological Applications* 21:2007–2015.
- Lave, R. 2009. The controversy over natural channel design: substantive explanations and potential avenues for resolution. *Journal of the American Water Resources Association* 45:1519–1532.
- Louhi, P., H. Mykrä, R. Paavola, A. Huusko, T. Vehanen, A. Mäki-Petäys, and T. Muotka. 2011. Twenty years of stream restoration in Finland: little response by benthic macroinvertebrate communities. *Ecological Applications* 21:1950–1961.
- Mayer, P. M., A. H. Todd, J. A. Okay, and K. A. Dwire. 2010. Introduction to the featured collection on riparian ecosystems and buffers I. *Journal of the American Water Resources Association* 46:207–210.
- Miller, J. R., and R. C. Kochel. 2010. Assessment of channel dynamics, in-stream structures and post-project channel adjustments in North Carolina and its implications to effective stream restoration. *Environmental Earth Sciences* 59:1681–1692.
- Miller, S. W., P. Budy, and J. C. Schmidt. 2010. Quantifying macroinvertebrate responses to in-stream habitat restoration: applications of meta-analysis to river restoration. *Restoration Ecology* 18:8–19.
- Niezdoga, S. L., and P. A. Johnson. 2005. Improving the urban stream restoration effort: identifying critical form and processes relationships. *Environmental Management* 35:579–592.
- Nilsson, C., C. A. Reidy, M. Dynesius, and C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308:405–408.
- O'Donnell, T. K., and D. L. Galat. 2007. River enhancement in the upper Mississippi River basin: approaches based on river uses, alterations, and management agencies. *Restoration Ecology* 15:538–549.
- Palmer, M. A. 2009. Reforming restoration: science in need of application and applications in need of Science. *Estuaries and Coasts* 32:1–17.
- Palmer, M. A., et al. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* 42:208–217.
- Palmer, M. A., H. L. Menninger, and E. Bernhardt. 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology* 55:205–222.
- Richter, B. D., and G. A. Thomas. 2007. Restoring environmental flows by modifying dam operations. *Ecology and Society* 12(1):12.
- Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific northwest catchments. *North American Journal of Fisheries Management* 22:1–20.
- Roni, P., K. Hanson, and T. Beechie. 2008. Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management* 28:856–890.
- Rood, S. B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppettone, S. Swanson, and P. L. Wagner. 2003. Flows for floodplain forests: a successful riparian restoration. *BioScience* 53:647–656.
- Rood, S. B., G. M. Samuelson, J. H. Braatne, C. R. Gourley, F. M. R. Hughes, and J. M. Mahoney. 2005. Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment* 3:193–201.
- Rosgen, D. L. 1994. A classification of natural rivers. *Catena* 22:169–199.
- Rosgen, D. L. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado, USA.

- Stanley, E. H., and M. W. Doyle. 2003. Trading off: the ecological removal effects of dam removal. *Frontiers in Ecology and the Environment* 1:15–22.
- Stromberg, J. C. 2001. Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism. *Journal of Arid Environments* 49:17–34.
- Sudduth, E. B., B. A. Hassett, P. Cada, and E. S. Bernhardt. 2011. Testing the Field of Dreams Hypothesis: functional responses to urbanization and restoration in stream ecosystems. *Ecological Applications* 21:1972–1988.
- Sundermann, A., S. Stoll, and P. Haase. 2011. River restoration success depends on the species pool of the immediate surroundings. *Ecological Applications* 21:1962–1971.
- Tullos, D. D., D. L. Penrose, G. D. Jennings, and W. G. Cope. 2009. Analysis of functional traits in reconfigured channels: implications for the bioassessment and disturbance of river restoration. *Journal of the North American Benthological Society* 28:80–92.
- Violin, C. R., P. Cada, E. B. Sudduth, B. A. Hassett, D. L. Penrose, and E. S. Bernhardt. 2011. Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. *Ecological Applications* 21:1932–1949.
- Walsh, C. J., T. D. Fletcher, and A. R. Ladson. 2005. Stream restoration in urban catchments through re-designing storm-water systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society* 24:690–705.
- Walters, C. J. 2007. Is adaptive management helping to solve fisheries problems? *Ambio* 36:304–307.
- Whiteway, S. L., P. M. Biron, A. Zimmermann, O. Venter, and J. W. A. Grant. 2010. Do in-stream restoration structures enhance salmonid abundance? A meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 67:831–841.
- Woolsey, S., et al. 2007. A strategy to assess river restoration success. *Freshwater Biology* 52:752–769.
- Yu, G. A., Z. Y. Wang, K. Zhang, X. H. Duan, and T. C. Chang. 2010. Restoration of an incised mountain stream using artificial step-pool system. *Journal of Hydraulic Research* 48:178–187.