Making Stream Restoration More Sustainable: A Geomorphically, Ecologically, and Socioeconomically Principled Approach to Bridge the Practice with the Science

ROBERT J. HAWLEY

Despite large advances in the state of the science of stream ecology and river mechanics, the practitioner-driven field of stream restoration remains plagued by narrowly focused projects that sometimes even fail to improve aquatic habitat or geomorphic stability—two nearly universal project goals. The intent of this article is to provide an accessible framework that bridges that gap between the current state of practice and a more geomorphically robust and ecologically holistic foundation that also provides better accounting of socioeconomic factors in support of more sustainable stream restoration outcomes. It points to several more comprehensive design references and presents some simple strategies that could be used to protect against common failure mechanisms of ubiquitous design approaches (i.e., regional curves, Rosgen planform, and grade control). From the simple structure design to the watershed-scale restoration program, this may be a first step toward a more geomorphically principled, ecologically holistic, and socioeconomically sustainable field.

Keywords: stream restoration, sustainability, ecological engineering, freshwater biology, geomorphology

he state of the practice of stream restoration includes sweeping variability across ecoregions, political jurisdictions, and practitioner groups (Bernhardt et al. 2005). Design philosophies range from "cookie-cutter" formbased methods to highly tailored process-based approaches that incorporate ecological and hydrogeomorphic drivers. Project stakeholders can encompass assortments of regulators, developers, environmentalists, recreationalists, city or infrastructure managers, property owners, and others. Spatial scales span from the single structure (e.g., less than a 10-meter reach) to the entire watershed, with goals extending from improved channel stability to the restoration of ecosystem processes. Project outcomes can fluctuate from actually degrading stream habitat (Smith SM and Prestegaard 2005) and biotic integrity (Palmer et al. 2010) to restoring a more natural flow regime and facilitating ecological improvement, such as expanded availability of habitat (Hawley et al. 2017) or improved water quality (Roley et al. 2012). Costs can range from less than \$1000 to more than \$1 billion (Jamison

2015) and are a poor predictor of project outcomes in many cases.

The most prevalent types of United States-based stream restoration activities typically focus on manipulating instream habitat via heavy construction (e.g., installing boulder structures, remeandering a channel via large-scale earth moving, and engaging in other activities requiring large equipment). Although the industry has experienced incremental shifts toward more geomorphically robust and ecologically viable approaches-for example, "River Styles" in Australia and New Zealand (Brierley and Fryirs 2005) and United Kingdom-based guidance centered on reducing runoff at the source (Environment Agency 2010)—a plurality of United States-based stream channel designers (perhaps even a majority?) organize their designs around three well-intended but fallible practices: regional curve dimensions, Rosgen (1994) planform pattern, and grade control structures to constrain the profile (i.e., "dimension, pattern, and profile"; see box 1). The popular form-based approach

BioScience 68: 517–528. © The Author(s) 2018. Published by Oxford University Press on behalf of the American Institute of Biological Sciences. This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/ by-nc/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact journals.permissions@oup.com doi:10.1093/biosci/biy048 Advance Access publication 7 June 2018

Box 1. Glossary of select terms.

Grade control structure: a structure composed of rocks and/or wood, intended to hold the vertical elevation of the stream constant at a given location. A structure intended to prevent vertical downcutting (e.g., figure 7).

Planform: the alignment of the stream channel when viewed from above (e.g., figure 8).

Regional curve: a "best-fit" line plotting the bankfull channel dimensions of reference streams from within the same region against their respective drainage areas (e.g., figure 2).

has resulted in large-scale failures in the United States (e.g., White Marsh Run; Soar and Thorne 2001), and it is widely observed that such failures could have been prevented with a more geomorphically principled design approach (Kondolf 2006, Simon et al. 2007, Doyle and Shields 2012). To help to bridge the gap between practitioners and researchers, one of the aims of this article is to convey the merits of incorporating a relatively simple geomorphic foundation into the design decision process to guide designers away from several common shortcomings associated with conventional geomorphic designs (e.g., excess floodplain and/or channel energy relative to resistance). A second goal is to veer practitioners toward more ecologically holistic outcomes by expanding the conventional focus of stream restoration projects and programs. Third, I will add to the expanding list of scientists and practitioners who advocate for a more explicit incorporation of socioeconomic factors into stream restoration projects, suggesting that it is in the best interest of long-term environmental progress. Together, this geomorphically principled, ecologically holistic, and socioeconomically sustainable approach presents a more viable future for the stream restoration industry (figure 1).

Geomorphically principled design

Across watershed, valley, and channel scales, an equilibrium stream balances its erosive forces with the available resistance. The dominant drivers of this balance (discharge, slope, sediment supply and size) were made conventional wisdom by Lane (1955), whose conceptual model has been a foundational reference for river researchers and educators for over 60 years. More recently, researchers have expanded the model to explain the qualitative responses of other variables such as width-to-depth ratio (e.g., Nanson and Huang 2008), sinuosity, and bedform amplitude (Dust and Wohl 2012), among other uses. Simply from the perspective of assessing the collective energy of a setting relative to its resistance, the framework can be amended to accommodate any alluvial setting by considering whether a variable contributes to or resists erosion (figure 2). For example, channel width, floodplain width, grade control, bank strength, and vegetation all contribute to the collective resistance of the setting, whereas channel depth, floodplain depth, and valley slope amplify the erosive power. Paradoxically, none of Lane's (1955) original drivers are explicitly incorporated into the commonly applied regional curve approach, in which

mean estimates of bankfull geometry are predicted as a function of drainage area on the basis of regression analysis of regional reference channels (figure 2). Only drainage area, typically considered a reasonable surrogate for discharge, attempts to indirectly account for one of Lane's original drivers. Bankfull dimensions such as width, depth, and crosssectional area are only a few of the metrics that influence erosion and resistance and are by no means as influential as Lane's original drivers (e.g., bed sediment size can affect the critical discharge for entrainment by orders of magnitude; Hawley and Vietz 2016) or even other factors such as valley slope (e.g., van den Berg 1995, Bledsoe and Watson 2001) or hardpoint or grade control spacing (e.g., Bledsoe et al. 2012, Hawley and Bledsoe 2013). Furthermore, regional equations typically come with standard errors that can substantially alter the energy and resistance in the channel and on the floodplain (e.g., Ohio's regional curves have standard errors ranging from approximately 20% to 30%; figure 2; Sherwood and Huitger 2005). This suggests that even if a given site was perfectly similar to the reference channels that informed the regional curve in all other factors influencing the adapted Lane framework, the representative "stable" dimensions for the site would fall somewhere in a relatively broad range. A "regional curve" channel constructed without regard for other dominant drivers of resistance and erosion in both the channel and the floodplain can be susceptible to geomorphic failure because of numerous mechanisms, such as rapid channel enlargement, floodplain denudation, and habitat degradation via sedimentation (figure 3), which can negatively affect other aspects of stream function, such as water quality and/or aquatic communities (Harman et al. 2012).

"In every respect, the valley rules the stream." —Hynes (1975)

Considering all drivers of fluvial erosion and resistance, the valley setting, in particular, exhibits a disproportionate influence on the biological and geomorphic character of the stream. Valley slope governs the amount of energy the flow can express on the channel and floodplain, whereas valley confinement determines the floodplain width available to dissipate that energy and the channel forms that the stream can occupy (Brierley and Fryirs 2009). The valley also plays an outsized role in the channel's ability to recruit coarse sediment—such as steep colluvial hollows (e.g., boulders) and glaciated alluvial valleys (e.g., cobbles or gravels) versus



Figure 1. A framework for sustainable stream restoration in which long-term biological integrity is dependent on both natural processes (adapted in part from the stream function pyramid of Harman et al. 2012) and socioeconomic factors, such as accommodating safe wading access or complementing the aesthetics of the neighborhood.

post-European settlement alluvium (e.g., fines)—as well as how resistant the valley and channel will be to both incision and lateral migration.

For example, tortuous meanders in broad, gentlesloped valleys, such as the Moraine Park section of the Big Thompson River (figure 4), are typically driven by resistance elements that diminish the channel's ability to downcut, such as a prevalence of coarse alluvial materials both in the channel and buried across the floodplain, shallow bedrock, and/ or dense vegetation. Although Rosgen (1994) mentioned the alluvial materials associated with his most sinuous ("E" type) channel classification (sinuosity of more than 1.5), many designers appear to overlook the role of valley or substrate resistance and focus more on Rosgen's numeric thresholds (e.g., "E" type channels have slopes of less than 2%).

Forensic engineering of the approximately \$5-million, 42-kilometer stream "re-establishment" (remeandering) and "enhancement" project undertaken for compensatory mitigation in central Kentucky, photographed in figure 3 (and subsequent photo examples throughout the article), underscores several common failure mechanisms, all of which are readily preventable if designers incorporate a more holistic accounting of energy and resistance across both the channel and the floodplain.

Explicitly consider floodplain resistance. Floodplains in stream restoration projects are often exclusively armored with

native vegetation such that their stability depends on limiting flood flow shear stress to the corresponding permissible threshold (typically approximately 5-10 kilograms per square meter; approximately 1-2 pounds per square foot) for unmowed stands of native grasses (Chen and Cotton 1988). Areas of floodplain erosion (figure 3) and chute cutoffs (figure 5) were typically limited to reaches where floodplain shear stress (valley slope combined with wrack line flood depths and the specific weight of water) exceeded approximately 5 kilograms per square meter, whereas floodplain vegetation remained largely intact in reaches where floodplain shear was limited to less than 5 kilograms per square meter. An integrated approach to channel and floodplain design could be used to optimize the size of the channel(s) such that floodplain shear stresses did not exceed vegetation thresholds for a defensible design flow that is agreeable to project stakeholders, such as the 100-year event, often with an additional factor of safety. In valleys too steep or confined to accommodate such reduced floodplain shear stresses, valley-wide grade control or other measures could be incorporated to reduce the risks and relative severity of floodplain erosion.

Consider secondary flows. Helical forces in meander bends can cause failures that wouldn't otherwise be reflected by conventional one-dimensional modeling. This can be especially evident at confluences (figure 5) as well as in valley- or stream-type transitions, including the beginning or ending of project reaches. Rather than presuming a valley setting and channel cross-section can accommodate an aggressive meander pattern, use a level of hydraulic modeling that is commensurate with the setting to evaluate erosive forces in bends relative to bank strength. In some cases, one-dimensional models with simple adjustments that account for bank angle (Julien 2002) or radius of curvature (Soar and Thorne 2001) may be adequate, whereas two-dimensional modeling may be warranted in other settings.

Conduct a complete accounting of reference channel resistance. Regional curves of reference stream geometry only explicitly account for channel geometry and drainage area (figure 2); however, there is often a large inventory of factors that drive the stability of such reference channels that is not reflected in regional curves. For example, reference streams in relatively steep valley settings often have an abundance of resistant bed material (figure 6), whereas practitioners commonly overlook the importance of providing sufficiently resistant bed material in their restored streams, often with an overreliance on grade control structures. Designers must be cognizant of the differences between reference stream settings and project settings (Niezgoda and Johnson 2005) and account for such differences in erosive forces and resistance in their designs.

Grade control structures must actually control the grade. With the nearly universal reliance on grade control structures



Figure 2. Equilibrium streams balance their erosive forces with resistance across watershed, valley, and channel scales. Regional curves, such as this power function representing bankfull width as a function of drainage area for 50 reference sites across nearly the entire state of Ohio (region A; Sherwood and Huitger 2005), typically include appreciable standard errors (as would be expected across large spatial scales and geomorphically diverse settings). Regional curve dimensions (bankfull width, depth, and area) are often the primary determinant in sizing remeandered streams, despite lacking explicit consideration of key drivers of erosive energy and resistance; the regional-curve approach only indirectly accounts for discharge via its surrogate (drainage area) and rarely has appreciable predictive power for the other three dominant drivers from Lane's (1955) original framework (bold text, Qs, d₅₀, Q, and S).

by most stream restoration practitioners, it is critical that those structures be designed and installed to provide long-term resistance. Particularly in design approaches that leave the channel little room or available materials for self-adjustment (e.g., figure 6), grade control designs must be robust enough to resist both downcutting and flanking, both of which are common failure mechanisms (figure 7; Smith SM and Prestegaard 2005). Practitioners are encouraged to size their grade control armor to actually resist entrainment at a defensible recurrence interval (e.g., Q_{100} with an approximately 25%–50% factor of safety) and provide adequate thicknesses of the stone layers both vertically and tied into the banks laterally (Chen and Cotton 1988, Julien 2002).

Additional geomorphic considerations. There are volumes of much more robust guidance related to geomorphic stability, including a long tradition of designing channels for sediment continuity, which is particularly important in settings with large sediment supplies (Biedenharn et al. 2000, Copeland et al. 2001, Soar and Thorne 2001), along with more recently expanded guidance that incorporates the full spectrum of discharges as opposed to a single dominant discharge (Bledsoe et al. 2016, Stroth et al. 2017). This forum is not intended to be a comprehensive design guide but rather an attempt to create awareness regarding common failures mechanisms of some ubiquitous design practices and to point designers toward a stronger geomorphic foundation such that they can understand why more robust design tools are warranted in certain settings. For example, in the relatively low sediment supply setting of the project detailed above, an array of relatively simple strategies could have provided a more comprehensive balance of energy and resistance and precluded such broadscale failures (figure 8). Although by no means an exhaustive list, such reachscale strategies need not sacrifice the functional benefits of the project: Even two-stage "ditches" have substantial nitrogen removal benefits over channelized streams (Roley et al. 2012). Furthermore, many of these relatively simple suggestions, including creating multiple flow paths and more high-quality habitat substrate such as LWD and cobbles, could result in a greater likelihood for ecological recovery over the long term (Jahnig and Lorenz 2008).

Ecologically holistic design

The fluvial geomorphic processes that are central to a river's role in shaping the landscape are by no means the only driver of ecosystem function. The "field of dreams" presumption that physically

reconstructed stream habitat will beget improved biotic integrity has often fallen short of such goals (Palmer et al. 2010). As Harman and colleagues (2012) synthesized, stream function depends on much more than qualitatively desirable habitat, because hydrologic, hydraulic, geomorphic, physicochemical, and biological processes can all drive stream function, both individually and collectively (figure 1). For example, the timing of flows that exceed the threshold discharge for bed material entrainment was the dominant driver of community composition in a 7-year study at a reference site, with biotic integrity falling from excellent to poor in a year with atypically large and frequent bed mobilizing events (Hawley et al. 2016). In reference streams where the habitat, water quality, and natural flow regime remain intact, the biotic and geomorphic recoveries that were tracked in the years following the excessive bed disturbance conform to the disturbance-recovery system dynamics emblematic of a robust ecosystem (e.g., Townsend et al. 1997). However, in watersheds with amplified rates of stormwater runoff and chronic bed disturbance, it is easy to envision how the altered flow regime exhibits both direct impacts on the biota, such as inducing drift or mortality, as well as indirect impacts, such as degraded, more homogenous habitat (Hawley et al. 2013, Vietz et al. 2014) and poorer water quality due to recruitment of fine sediment loads from amplified rates of bank erosion (Simon and Klimetz 2008, Russell et al. 2017). In evolutionarily driven systems dependent on such a broad array of mechanistic drivers, biotic recovery clearly depends on a more holistic approach in systems that are affected by more than simply degraded habitat.



Figure 3. Regional curve designs can be susceptible to failure due to numerous mechanisms, including a lack of consideration of floodplain flows and associated shear-stress thresholds for vegetation. Photograph from a compensatory mitigation project in central Kentucky by the author.



Figure 4. Big Thompson River in Moraine Park of Rocky Mountain National Park (sinuosity approximately 1.7, valley slope approximately 0.8%) would be considered an "E" type channel in the Rosgen (1994) classification system. Designers that attempt to mimic this planform style in valleys up to 2% slope (Rosgen 1994) but lacking comparable sediment sizes and supplies, bank resistance, and floodplain armoring (i.e., buried cobbles throughout the entire valley) can be susceptible to instability via lateral migration, grade control flanking, channel downcutting, chute cutoffs, and floodplain erosion. Photograph by the author.



Figure 5. Erosive forces can often be amplified in bends and at confluences warranting specific analyses (e.g., twodimensional modeling) of whether the bank material is adequate to resist erosion. Energy-dissipation pools; extra grade control, bank, or floodplain armor; and/or a more down-valley orientation with a longer radius of curvature are all strategies that could have helped to reduce the risk of the chute cutoff at this confluence. Photograph by the author.

"Streams not just as things in space but processes through time." —Bledsoe and colleagues (2008)

An ecologically holistic approach must not only consider the temporal interplay of present-day stream processes such as energy sources and water-quality processes but must also consider the historical context of the landscape. As Wohl and Merritts (2007) described, very few river networks are likely to be in a truly "natural" state, and the legacy effects from a long history of manipulation extend far beyond stream channelization and valley infills of postsettlement alluvium (figure 9). For example, the denuded hillslopes, degraded soils, and drained wetlands and floodplains likely have persistent hydrologic impacts in many watersheds such that even a partially recovered and forested watershed could likely benefit from hydrologic restoration efforts as much as in-stream habitat restoration projects. The catchment-scale focus on restoration of ecological processes is nearly conventional wisdom in scientific circles (Walsh et al. 2005) but has experienced comparatively few implementation efforts relative to in-stream habitat restoration.

As aquatic resources, stream ecosystems are probably most dependent on the natural flow regime (Poff et al. 1997) such that hydrologic restoration is a prerequisite for facilitating recovery of ecological functions. Moreover, hydrologic restoration has the capacity to send cascading benefits through the entire receiving stream network, whereas reachbased habitat restoration has a more restricted potential to propagate benefits up or downstream. For example, a recent hydrologic restoration pilot project by Hawley and colleagues (2017) showed that by retrofitting a conventional detention basin outlet to restrict discharges below the threshold flow for erosion in the receiving channel, a concurrent benefit was the conversion of the stream from one that used to go dry approximately 10% of the time to a perennial resource with pools supportive of native minnows observed during seasonal low flow periods. It's difficult to envision a comparable level of ecological recovery from a conventional in-stream habitat restoration project with a similar budget of approximately \$10,000.

What's more, hydrologic restoration and habitat rehabilitation need not be mutually exclusive. Indeed, incorporating hydrologic restoration actions into conventional habitat restoration projects may present some of the most costeffective opportunities for large-scale hydrologic restoration. Groundwater dams, bankfull wetlands, vernal pools, and other floodplain restoration strategies are likely to add relatively little costs to conventional stream restoration projects and may even facilitate compliance with success criteria on regulated stream mitigation projects by promoting groundwater levels that are more supportive of the establishment of native herbaceous ground cover and potentially suppressive of some invasive species (Rob Lewis, Kentucky Department of Fish and Wildlife Resources, Wetland and Stream Mitigation Program, Frankfort, Kentucky, personal communication, 1 August 2016).

By having at least a foundational understanding of the historic landscape, restoration practitioners may more readily incorporate actions (both large and small) that are restorative of ecosystem processes into conventional habitat restoration programs. For example, the natural flow (Poff et al. 1997), sediment (Wohl et al. 2015), and wood (Wohl 2011) regimes are likely to be essential components of ecosystem restoration. By focusing on restoring ecosystem processes as opposed to forms (Beechie et al. 2010), actions that one might not conventionally classify as restoration may actually present the greatest restorative potential for the lowest cost. For example, this could include restoration of important biotic controls (Polvi and Wohl 2013), such as reintroduction (or discontinued extirpation) of beavers in low-energy floodplain systems with incised channels (e.g., Pollock et al. 2007) or the placement of ramped, in-stream wood (Davidson et al. 2015, Yochum 2016) with minimal equipment and disturbance to the existing stream, riparian habitat or canopy cover, leaving in place existing energy sources, temperature mediation, and future sources of instream wood while enhancing bank stability and promoting in-stream processes such as bar development and habitat diversification (Collins and Montgomery 2002).

Socioeconomic sustainability

By most definitions, sustainability implies both ecological and socioeconomic domains (e.g., James et al. 2015, Wandemberg 2015). The latter has been largely overlooked but is increasingly seen as an equally important pillar of stream restoration success. RF Smith and colleagues (2016)



Figure 6. Reference streams in moderately steep valleys often have an abundance of resistant bed material in the channel and buried in the adjacent floodplain (right photo). Regional curve designs (left photo) often attempt to match benchfull geometries of reference channels without providing commensurate resistance in the channel or the floodplain (note the absence of coarse bed material). Photographs by the author taken from the same compensatory mitigation project in central Kentucky in valleys with similar slopes, widths, and drainage areas, with the "re-establishment" reach (left photo) draining approximately 0.2 square kilometer and the "preservation" reach (right photo) draining approximately 0.3 square kilometer.

made the case that it's actually in the best interest of environmental progress for projects to intentionally incorporate social factors such as access, aesthetics, and flood concerns. For example, accommodating safe access to even degraded streams such as at Big Rock Park in Louisville, Kentucky, with relatively poor water quality and habitat provides substantial environmental value by providing wading access for the local community. Several local and national officeholders supportive of stream restoration programs had some of their first exposures to natural streams in this park.

Given the prevalence of stream burial in urban areas (Roy et al. 2009), particularly in socioeconomically depressed neighborhoods with little access to safe recreation, urban stream daylighting in conjunction with park creation and urban renewal may have much lower costs per person benefited than comparable rural projects despite requiring larger capital investments. Neale and Moffett (2016) recently suggested that even intermittently open stream networks may be much more biologically productive than totally buried streams, and the same has been documented for water-quality functions such as nitrogen cycling (Beaulieu et al. 2014). Particularly if daylighting can strike a balance of adding value without inducing dislocation via gentrification (e.g., Wolch et al. 2014), the stream restoration strategy may provide socioeconomic and ecological benefits that help to address environmental-justice issues in an equitable and culturally sensitive way.

With the goal of restoring ecological processes as well as creating socioeconomic benefits, even seemingly disparate programs such as urban heat island mitigation through urban reforestation can play an important role in watershedscale stream restoration. A more sustainable approach to stream restoration could convert socioeconomic "barriers" into opportunities that create greater collective benefits for both society and aquatic ecosystems. And a more geomorphically principled approach to in-stream habitat manipulation will help to mitigate the negative perceptions associated with projects that have widespread erosion and are often viewed as "failures."

Beyond more positive socioeconomic *outcomes*, it is also critical to recognize the influence of socioeconomic *processes* in enabling sustainable restoration projects. A stormwater

Forum



Figure 7. Flanking, entrainment, and inadequate rock layer thicknesses are all common failure mechanisms of grade control structures. Much of the rock from the riffle structures in this reach had been mobilized relatively soon after construction (aerial photo, yellow arrows), indicating a lack of adequate sizing of the stone to resist entrainment. Ground photo by the author, aerial photograph by P. Tower, Sustainable Streams.

separation or stream daylighting project in Cincinnati, Ohio, exemplifies an array of socioeconomic processes that converged on a more sustainable approach to the city's legally mandated sewer overflow mitigation investments. The daylighting approach was selected over the alternative tunneling approach, which exclusively focused on increasing the amount of combined sewer storage underground. By contrast, the daylighting approach restores hydrological processes by keeping stormwater out of the combined sewer and routing it to a reconstructed channel in a valley where the stream had been buried for approximately 100 years. Not only was the tunneling approach estimated to cost approximately \$170 million more than the daylighting alternative, but also the public engagement and decision-making process resulted in an overwhelming preference of the daylighting approach at a rate of more than 9 to 1 (Hawley et al. 2015). And even with the favorable economics and support of local residents and community groups, sustained efforts of project champions at the sewer utility were essential in shepherding the project through complex governance structures, along with a willingness of regulators to embrace an unconventional approach to overflow mitigation.

I have also witnessed the socioeconomics become the driving force toward more sustainable outcomes on compensatory mitigation projects, for example, which require permanent conservation easements along the stream corridors. Rather than purchasing easements only along the stream corridor, the Kentucky Department of Fish and Wildlife Resources (KDFWR) has purchased entire watersheds for several stream projects. The surrounding catchments are converted into KDFWR Wildlife Management Areas, which create public areas for responsible fishing and hunting and permanently protect the landscape from future development. The approach also creates more opportunities for hydrologic restoration throughout the drainage network while meeting institutional goals of expanded wildlife habitat with public access. These short case studies across urban and rural settings with a diverse range of stakeholders reinforce the role of socioeconomics as the base of the pyramid in the proposed framework presented herein (figure 1).

Conclusions

In conclusion, the proposed bottom-up framework (figure 1) suggests that a more complete accounting of socioeconomic factors and processes is in the best interest of aquatic habitat restoration because it creates the foundation for both better outcomes on individual projects and more sustained support for future restoration efforts. Wherever feasible, such efforts should also prioritize the next level of the pyramid, hydrologic restoration (figure 9), which can have cascading benefits through other elements of stream function in both space and time, such as expanded availability of stable habitat and long-term hydrographs more aligned with life histories of native flora and fauna. Moving up the pyramid, an iterative hydraulic-geomorphic design process can ensure that both the channel and floodplain are dimensioned to sufficiently resist the stresses and velocities they will experience during floods. In higher-energy settings, this may require valley-wide grade control (figure 8b) and/or other means (figure 8h) to protect against excess floodplain erosion (figure 3), chute cutoffs (figure 5), channel grade control flanking (figure 7), and other common failure mechanisms. For example, encouraging frequent floodplain inundation promotes contact with vegetated surfaces and associated ecohydologic and water-quality processes, but standardizing a simple check of floodplain shear stress could go far in preventing instabilities that arise from putting too much water on an unarmored vegetated surface. In summary, using good engineering judgment to undertake a complete accounting of the valley or channel energy and resistance is a practical way to apply the principles of Lane's (1955) balance to any setting. No one framework can arrest all the shortcomings of an industry, but it is my hope that this framework results in more geomorphically principled designs that are less prone to common failures, as well as more sustainable stream restoration programs that can systematically create greater ecosystem and socioeconomic benefits.

Acknowledgments

RJH received no direct funding to draft this article. The views expressed in this forum are the views of the author alone and do not reflect the views of his professional clients or funding sources. The photos used to underscore some of



Figure 8. A broad array of relatively simple, low-cost, reach-scale strategies could have been employed to facilitate a more comprehensive balance between erosion and resistance, including (a) using large woody debris and brush piles to provide floodplain roughness, trap sediment, and dissipate energy during flood flows, which could be particularly beneficial immediately following construction before herbaceous vegetation becomes well established; (b) providing valley-wide grade control to better resist against incision in both the channel and the floodplain and commonly applied by the University of Louisville Stream Institute (Art Parola, University of Louisville Stream Institute, Louisville, Kentucky, personal communication, 10 September 2009); (c) designing a more irregular planform to deflect the potential chute cutoff path (the straight line linking the bends between one full meander wavelength) from a perfectly down-valley orientation; (d) designing intentional secondary channels with sufficient armoring to resist erosion and, when combined with the main channel, providing enough conveyance capacity to reduce shear stresses on the floodplain below the permissible threshold for the vegetative cover; (e) incorporating more stone and/or large woody debris in the channel bed and extending the grade control armor into the banks to protect against flanking; (f) designing a large enough channel cross-section to limit the floodplain shear stress to a threshold less than that of native vegetation; (g) using an irregular valley cross-section, such as a two-stage channel and/or a steeper cross slope, to keep the most erosive portion of the flow column directed toward the channel and intentionally meander the dominant flow path during flood flows (as opposed to uniformly traveling down-valley over an unprotected floodplain); and (h) using combinations of geomorphically principled strategies, good judgment, and value engineering to provide the most optimal reach-scale design for the setting.

the common failure mechanisms discussed herein (figures 3, 5, 6, and 7) were all from the same 42-kilometer reestablishment and rehabilitation project in central Kentucky during the first year of monitoring following completion of construction. Remedial actions by the design-build team were ongoing at the time of submission. A minimum of 4 additional years of monitoring will be completed to document the outcomes of the compensatory mitigation project in support of the final determination of mitigation credits. These photos are by no means a reflection of the typical outcomes of Kentucky's fee-in-lieu-of (FILO) projects but were representative of several common mechanisms on one FILO project and have been observed on numerous other non-FILO projects.

The author would like to thank numerous mentors and collaborators who have contributed to the collective experiences that informed this article, especially Brian Bledsoe, Kurt Cooper, Nora Korth, Rob Lewis, Katie MacMannis, and Art Parola. I am very grateful to Eric Dawalt, Kyle McKay, and one anonymous reviewer who offered



Figure 9. A schematic of (a) a pre-European settlement, (b) a post-European settlement, and (c) present-day hydrologic networks and corresponding cross-sections in a hypothetical alluvial valley in a humid-temperate watershed, with dominant responses and characteristics (adapted from Hawley 2012).

extremely constructive reviews, along with the handling editor and the editor in chief, Scott Collins, whose contributions substantially strengthened the article.

Supplemental material

Supplementary data are available at *BIOSCI* online.

References cited

- Beaulieu JJ, et al. 2014. Effects of urban stream burial on organic matter dynamics and reach scale nitrate retention. Biogeochemistry 121: 107–126.
- Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Roni P, Pollock MM. 2010. Process-based principles for restoring river ecosystems. BioScience 60: 209–222.

- Bernhardt ES, et al. 2005. Synthesizing US river restoration efforts. Science 308: 636–637.
- Biedenharn DS, Copeland RR, Thorne CR, Soar PJ, Hey RD, Watson CC. 2000. Effective Discharge Calculation: A Practical Guide. US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Report no. ERDC/CHLI TR-00-15.
- Bledsoe BP, Watson CC. 2001. Logistic analysis of channel pattern thresholds: Meandering, braiding, and incising. Geomorphology 38: 281–300.
- Bledsoe BP, Hawley RJ, Stein ED. 2008. Stream Channel Classification and Mapping Systems: Implications for Assessing Susceptibility to Hydromodification Effects in Southern California. Southern California Coastal Water Research Project.
- Bledsoe BP, Stein ED, Hawley RJ, Booth DB. 2012. Framework and tool for rapid assessment of stream susceptibility to hydromodification. Journal of the American Water Resources Association 48: 788–808.

- Bledsoe BP, Baker DW, Nelson PA, Rosburg T, Sholtes J, Stroth TR. 2016. Design Hydrology for Stream Restoration and Channel Stability at Stream Crossings. Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine. National Cooperative Highway Research Program. Project no. 24–40.
- Brierley GJ, Fryirs KA. 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell.
- ——. 2009. Don't fight the site: Three geomorphic considerations in catchment-scale river rehabilitation planning. Environmental Management 43: 1201–1218.
- Chen YH, Cotton GK. 1988. Design of Roadside Channels with Flexible Linings. US Department of Transportation, Federal Highway Administration. Report no. FHWA-IP-87-7, HEC 15.
- Collins BD, Montgomery DR. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology 10: 237–247.
- Copeland RR, McComas DN, Thorne CR, Soar PJ, Jonas MM, Fripp JB. 2001. Hydraulic Design of Stream Restoration Projects. US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Report no. ERDC/CHL TR-01-28.
- Davidson SL, MacKenzie LG, Eaton BC. 2015. Large wood transport and jam formation in a series of flume experiments. Water Resources Research 51: 10065–10077.
- Doyle MW, Shields FD Jr. 2012. Compensatory mitigation for streams under the clean water act: Reassessing science and redirecting policy. Journal of the American Water Resources Association 48: 494–509.
- Dust D, Wohl E. 2012. Conceptual model for complex river responses using an expanded Lane's relation. Geomorphology 139–140: 109–121.
- Environment Agency. 2010. The Fluvial Design Guide. Environment Agency. (10 May 2018; http://evidence.environment-agency.gov.uk/ FCERM/en/FluvialDesignGuide.aspx)
- Harman WA, Starr R, Carter M, Tweedy K, Clemmons M, Suggs K, Miller C. 2012. A Function-Based Framework for Stream Assessment and Restoration Projects. US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds. Report no. EPA 843-K-12-006.
- Hawley RJ. 2012. A regionally-calibrated approach to "channel protection controls"—How meeting new stormwater regulations can improve stream stability and protect urban infrastructure. Pages 997–1011 in Jaworski L, Tam W, eds. Stormwater Symposium. Water Environment Federation.
- Hawley RJ, Bledsoe BP. 2013. Channel enlargement in semi-arid suburbanizing watersheds: A southern California case study. Journal of Hydrology 496: 17–30.
- Hawley RJ, Vietz GJ. 2016. Addressing the urban stream disturbance regime. Freshwater Science 35: 278–292.
- Hawley RJ, MacMannis KR, Wooten MS. 2013. Bed coarsening, riffle shortening, and channel enlargement in urbanizing watersheds, northern Kentucky, USA. Geomorphology 201: 111–126.
- Hawley RJ, Lyons J, Wolnitzek G, Lodor ML. 2015. Stream daylighting—A viable CSO mitigation strategy. World Water: Stormwater Management 3: 17–19.
- Hawley RJ, Wooten MS, MacMannis KR, Fet EV. 2016. When do macroinvertebrate communities of reference streams resemble urban streams? The biological relevance of Qcritical. Freshwater Science 35: 778–794.
- Hawley RJ, Goodrich JA, Korth NL, Rust CJ, Fet EV, Frye C, MacMannis KR, Wooten MS, Sinha R. 2017. Detention outlet retrofit device improves the functionality of existing detention basins by reducing erosive flows in receiving channels. Journal of the American Water Resources Association 53: 1032–1047.
- Hynes HBN. 1975. The stream and its valley. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 19: 1–15.
- Jahnig SC, Lorenz AW. 2008. Substrate-specific macroinvertebrate diversity patterns following stream restoration. Aquatic Sciences 70: 292–303.
- James P, Magee L, Scerri A, Steger M. 2015. Urban sustainability in theory and practice. Routledge.

- Jamison P. 2015. Army Corps board approves \$1.3-billion L.A. River restoration proposal. Los Angeles Times (1 July 2015; www.latimes.com/ local/lanow/la-me-ln-army-corps-l-a-river-restoration-20150716-story. html)
- Julien PY. 2002. River Mechanics. Cambridge University Press.
- Kondolf GM. 2006. River restoration and meanders. Ecology and Society 11: 42-59.
- Lane EW. 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. US Department of the Interior Engineering Laboratories. Hydraulic Laboratory Report no. 372.
- Nanson GC, Huang, HQ. 2008. Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. Earth Surface Processes and Landforms 33: 923–942.
- Neale MW, Moffett ER. 2016. Re-engineering buried urban streams: Daylighting results in rapid changes in stream invertebrate communities. Ecological Engineering 87: 175–184.
- Niezgoda SL, Johnson PA. 2005. Improving the urban stream restoration effort: Identifying critical form and process relationships. Environmental Management 35: 579–592.
- Palmer MA, Menninger HL, Bernhardt ES. 2010. River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? Freshwater Biology 55: 205–222.
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: A paradigm for conservation and restoration of river ecosystems. BioScience 47: 769–784.
- Pollock MM, Beechie TJ, Jordan CE. 2007. Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32: 1174–1185.
- Polvi LE, Wohl EE. 2013. Biotic drivers of stream planform: Implications for understanding the past and restoring the future. BioScience 63: 439–452.
- Roley SS, Tank JL, Stephen ML, Johnson LT, Beaulieu JJ, Witter JD. 2012. Floodplain restoration enhances denitrification and reach-scale nitrogen removal in an agricultural stream. Ecological Applications 22: 281–297.
- Rosgen DL. 1994. A classification of natural rivers. Catena 22: 169-199.
- Roy AH, Dybas AL, Fritz KM, Lubbers HR. 2009. Urbanization affects the extent of hydrologic permanence of headwater streams in a Midwestern US metropolitan area. Journal of the North American Benthological Society 28: 911–928.
- Russell KL, Vietz GJ, Fletcher TD. 2017. Global sediment yields from urban and urbanizing watersheds. Earth-Science Reviews 168: 73–80.
- Sherwood JM, Huitger CA. 2005. Bankfull Characteristics of Ohio Streams and Their Relation to Peak Streamflows. US Department of the Interior, US Geological Survey.
- Simon A, Klimetz L. 2008. Relative magnitudes and sources of sediment in benchmark watersheds of the Conservation Effects Assessment Project. Journal of Soil and Water Conservation 63: 504–522.
- Simon A, Doyle M, Kondolf M, Shields FD Jr, Rhoads B, McPhillips M. 2007. Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response. Journal of the American Water Resources Association 43: 1117–1131.
- Smith RF, et al. 2016. Urban stream renovation: Incorporating societal objectives to achieve ecological improvements. Freshwater Science 35: 364–379.
- Smith SM, Prestegaard KL. 2005. Hydraulic performance of a morphologybased stream channel design. Water Resources Research 41 (art. W11413).
- Soar PJ, Thorne CR. 2001. Channel Design for Meandering Rivers. US Army Corps of Engineers. Report no. ERDC/CHL CR-01-1.
- Stroth TR, Bledsoe BP, Nelson PA. 2017. Full spectrum analytical channel design with the capacity/supply ratio (CSR). Water 9 (art. 271).

Forum

- Townsend CR, Scarsbrook MR, Doledec S. 1997. The intermediate disturbance hypothesis, refugia, and biodiversity in streams. Limnology and Oceanography 42: 938–949.
- Van den Berg JH. 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology 12: 259–279.
- Vietz GJ, Sammonds MJ, Walsh CJ, Fletcher TD, Rutherfurd ID, Stewardson MJ. 2014. Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness. Geomorphology 206: 67–78.
- Walsh CJ, Fletcher TD, Ladson AR. 2005. Stream restoration in urban catchments through redesigning stormwater systems: Looking to the catchment to save the stream. Journal of the North American Benthological Society 24: 690–705.

Wandemberg JC. 2015. Sustainable by Design. Createspace.

Wohl EE. 2011. Seeing the forest and the trees: Wood in stream restoration in the Colorado Front Range, United States. Pages 399–418 in Simon A, Bennett SJ, Castro JM, eds. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. American Geophysical Union.

- Wohl EE, Merritts DJ. 2007. What is a natural river? Geography Compass 1: 871–900.
- Wohl EE, Bledsoe BP, Jacobson RB, Poff NL, Rathburn SL, Walters DM, Wilcox AC. 2015. The natural sediment regime in rivers: Broadening the foundation for ecosystem management. BioScience 65: 358–371.
- Wolch JR, Byrne J, Newell JP. 2014. Urban green space, public health, and environmental justice: The challenge of making cities "just green enough." Landscape and Urban Planning 125: 234–244.
- Yochum SE. 2016. Guidance for Stream Restoration and Rehabilitation. US Department of Agriculture, Forest Service, National Stream and Aquatic Ecology Center. Technical Note no. TN-102.2.

Robert J. Hawley (bob.hawley@sustainablestreams.com) is the principal at Sustainable Streams, LLC, in Louisville, Kentucky. He is an experienced stream restoration designer and licensed professional engineer in several states, including active projects funded through the Fee-In-Lieu-Of (FILO) Stream Mitigation Program in Kentucky, as well as 303(d) grant-funded projects and projects with Municipal and private clients.