Riverine Habitats
25. Stream Restoration

DEFINITION

A *stream*, also known as a *branch*, *creek*, *run*, or *brook*, is a continuous surface flow of freshwater within a channel that is smaller than a river. Headwater streams can originate from groundwater (springs), runoff, or a wetland. Streams and rivers flow more than 3.5 million miles across the United States and are present in every region (EPA 2013). Streams are generally too small to have their own floodplain and run at steeper gradients and faster velocities than rivers, resulting in a greater amount of dissolved oxygen (USGS 2018). Nationally, stream health is declining as a result of an increase in impervious surfaces, polluted stormwater runoff, nutrient pollution, drought, deforestation, and physical barriers. As a response to this decline, communities are working to restore streams, with more than $1 billion a year spent on stream and river restoration in the United States (Bernhardt et al. 2005). Stream restoration techniques fall into two categories: form-based (which is more common) and process-based (Roni et al. 2002). Common techniques include brush layering, coir log installations, cross vanes, grading stream banks, log vanes, J-hooks, and step pools (MCDEP 2023).

TECHNICAL APPROACH

Form-based restoration involves physically manipulating the components of a stream to restore it to its natural morphology. This approach has many benefits, including enhancing fish habitat, reducing erosion, controlling water flow, and improving water quality. On the other hand, process-based restoration focuses on restoring the ecological interactions that occur in the stream, primarily by balancing biogeochemical cycles and enhancing organism movement. Given that stream ecology is heavily influenced by surrounding land uses, the scope of process-based restoration often reaches beyond the banks of the stream (Wohl et al. 2015).

Form-Based Restoration

- **Brush layering:** *Brush layering* involves taking small pieces of live cuttings from native plants and placing them at the bottom of a small terrace along the stream. The top of the cuttings should barely protrude from the ground, catching runoff and sediments. Eventually, live cuttings will begin to regenerate, growing roots and leaves and creating a living mat to protect the stream (Bischetti et al. 2010).
- **Coir logs:** A *coir log*, a type of geotextile, is a mesh netting made of coconut fibers that helps reduce erosion. Used in other nature-based solutions such as living shorelines (see summary), coir logs are biodegradable while holding soil in place and promoting plant growth. Coir logs are placed at the base of steep stream banks to keep them from eroding (Unser et al. 2009).

- **Cross vanes:** Building a cross vane involves placing a group of stones in a U shape across the width of the stream. The bottom of the U should be facing upstream. This directs the water toward the center of the stream, reducing erosion from water lapping up against the banks. Cross vanes also establish grade control by creating a slight elevation difference between the upstream and downstream portions of the structure (Gordon et al. 2013).
- **Regrading stream banks:** Steep slopes increase the amount of runoff that enters a stream, increasing the amount of water-borne pollutants and likelihood of flooding. Regrading steam banks entails terracing the banks into a series of small, gently sloping banks. Native vegetation can then be replanted to increase water retention (Figure 1). This results in reduced erosion and higher levels of groundwater recharge (Bernhardt and Palmer 2007).
- **Beaver management and beaver dam analogs (BDAs):** Beaver engineering profoundly reshapes the morphology of streams, creating wetlands and a diverse array of channel sizes. Maintaining a population of beavers enhances stream health, even in urban areas (Bailey et al. 2019). In areas where no beavers are present, building a BDA can replicate many of the same benefits of natural beaver dams. For more information on beavers, please see the beaver management and BDA summary.

Figure 25.1 A regraded and planted stream bank at Raccoon Creek, GA

Photo courtesy US Fish and Wildlife Service Southeast Region

- **J-hooks:** *J-hooks* are similar to cross vanes, but only span half of the stream. A J-hook has holes in between its rocks, allowing fast-flowing water to move through and creating a pool of stagnant water for aquatic organisms to live in. Reduced erosion and stream water velocity are additional J-hook benefits (Toran et al. 2012).
- **Log vanes:** In a log vane, large logs are placed across the stream, directing water flow away from an eroding bank. This results in the formation of scour flows directly below the log, providing habitat for aquatic organisms (MCDEP 2023).
- **Rock pack:** In streams that experience large runoff flows, trees along the bank of the stream can often be destabilized. Large stones can be placed around the base and roots of the tree to prevent it from falling into the stream (NRCS 2012).
- **Root wads:** A *root wad* refers to the tangle of roots that is often exposed in a downed tree, accompanied by the tree's stump. Root wads can be placed along a stream bank to protect the bank and provide habitat (Doll et al. 2003).
- **Step pools:** *Step pools* are a staircase-like configuration of rocks that slow down the stream flow over steep gradients. It is important to ensure that individual steps are not too high (above 30 cm), as this will promote undercutting and block fish passage (Purcell et al. 2002).
- **Stone toe protection:** Similar to other bank protection strategies, stone toe protection reduces the amount of runoff that enters the stream. A row of large stones is placed at the bank of the stream, protecting the bank from erosion and helping to reform the bank into a gentler slope (Shields et al. 1998).
- **Woody debris:** *Woody debris*, which encompasses large wood deposits and engineered log jams, serves the purpose of redirecting stream water into braided channels, slowing stream flow and providing fish habitat. Woody debris structure designs vary widely, but generally involve anchoring pieces of wood to a stream bank (Abbe et al. 2018).

Process-Based Restoration

- **Removing anthropogenic barriers in streams:** There are more than 2 million barriers to rivers and streams across the United States, inhibiting the flow of fish, nutrients, sediment, and water. This severely alters the processes that drive the stream and affect temperature and dissolved oxygen levels (Higgs 2002). Stream barriers, including small dams, weirs, culverts, and sluice gates, can be removed to restore the ecological benefits of the stream. This process is becoming increasingly common, with 65 dams being removed in the United States in 2023 alone (Thomas-Blate 2023). For technical guidance on the process of stream barrier removal, please see the riverine connectivity restoration summary.
- **Delineating a stream migration corridor:** Streams naturally migrate over time as their channel morphology changes. However, this migration is frequently blocked by infrastructure close to the stream. Proactively purchasing and maintaining natural lands around streams helps sustain the migration process, as well as reducing flood risk for surrounding structures. This gives streams the space to heal themselves, facilitating natural changes to stream morphology (Biron et al. 2014).

- **Reducing nutrient pollution:** Limiting the amount of nutrient pollution that enters a stream is a critical component of restoring stream health. This primarily done by planting riparian buffers, which are highly effective at capturing nutrient pollution (Vietz et al. 2016). For more detailed information on planting riparian buffers, please see the riparian buffer restoration summary.

These techniques can be implemented alone or in tandem with other approaches. One activity that cross-cuts many stream restoration projects is replanting native species. Native plants are used to reduce erosion on steep slopes and restore aquatic habitats within streams. A variety of planting techniques are used, including live cuttings, seeds, and planting plugs (Selvakumar et al. 2010).

Like many aquatic ecosystems, streams are prone to being overrun by invasive species. Streams are especially susceptible to invasive species because they are often located in urban environments, which enable conditions that favor these species. Invasive species can be removed either before or after the primary restoration activities, with many managers waiting until after the project to see if the new stream conditions will naturally eradicate the invasives. Common invasive species in streams include purple loosestrife (*Lythrum salicaria*), water thyme (*Hydrilla*), and goldfish (*Carassius auratus*) (Sulpizio 2020).

OPERATIONS AND MAINTENANCE

Stream restoration projects require regular trash and debris removal, especially after flood events. Invasive species management may also be required. Woody debris will likely need to be replaced every other year. Some restoration sites experience erosion issues and may need to be replanted.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Low gradients:** While many streams naturally flow at high gradients, stream restoration projects generally focus on low-gradient streams because they are less risky. The morphology of low gradients can be more easily manipulated without risking catastrophic erosion (Miller and Kochel 2010).

- ✓ **Cohesive banks:** *Cohesive banks* refers to stream banks with high quantities of clay or silt sediments. Restoration projects with cohesive banks have had greater success rates in the past because of their compatibility with in-stream structures such as cross vanes (Miller and Kochel 2010).

- ✓ **Bank erosion:** Bank erosion is one of the primary processes that stream restoration is attempting to reverse. Siting a project in an area with bank erosion will help magnify the benefits by preventing excess sediment from entering the stream. However, it is important to determine the source of bank erosion before starting the project, as a poorly designed restoration project can exacerbate the problem (NRCS 2007).

- ✓ **Near sources of nutrient pollution:** Nutrient pollution enters a watershed primarily through small streams. Restoring first- to third-order streams near sources of nutrient pollution such as agricultural fields maximizes the amount of nutrient pollution averted. Furthermore, smaller streams are generally simpler to restore, with less resources needed to build in-stream structures (Craig et al. 2008).

- ✓ **Large amounts of impervious surfaces:** Impervious surfaces block precipitation from percolating into the ground, increasing the amount of runoff that a stream must handle. Strengthening the ecological resiliency of the stream via restoration will allow it to better handle these increased flows (Sweeney et. Al. 2013).
- ✗ **Downstream of large sediment supplies:** While a stable sediment supply is necessary to prevent erosion of the stream, excess sediment causes problems by changing channel form. Recent housing developments, landslides, and eroded banks with little vegetation further upstream will impact the restoration site with excess sediment (Miller and Kochel 2010).
- ✗ **High stream power:** High stream power exacerbates current erosion problems, making them more difficult to remediate. This also makes it more difficult to build in-stream structures and direct water to the appropriate places (Miller and Kochel 2010).
- ✗ **Stream barriers that will not be removed as a part of the project:** Stream barriers will inhibit water flow and the transport of nutrients and sediment, preventing the stream from functioning in its natural state. If a stream barrier is located near the project site, then it is not worth investing the resources in restoration only to see the benefits masked (Rinaldi and Johnson 1997).
- ✗ **Streams running through wetlands:** Wetlands alter the flow regime of streams by slowing down and dispersing the water. The techniques mentioned in this summary were not designed for this environment. For more information on restoring inland wetlands, please see the inland wetlands summary.
- ✗ **Poor access:** Access to many smaller, forested streams can be difficult, often resulting in the felling of trees to make room for heavy machinery to reach the restoration site. In these scenarios, the environmental impacts of restoration often outweigh the benefits, making these sites poor choices for restoration.

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Stream Restoration: A Natural Channel Design Guidebook	Guidebook	2003	NC State University, NC A&T University, North Carolina Sea Grant	National	This guide covers siting, designing, and monitoring stream restoration projects to maximize ecological benefits. Additional topics covered include installing riparian buffers, flood studies, and an introduction to fluvial processes.	✓	✓	✓	—
Stream Restoration Design Field Guide	Guidebook	2008	US Department of Agriculture Natural Resources Conservation Service (NRCS)	National	Filled with diagrams illustrating specific stream restoration techniques, this guide provides helpful design ideas. The designs cover numerous strategies, including determining rock size, bank stabilization, and redirecting water flow.	✓	—	—	—
Large Wood Design Guidelines—National Manual	Guidebook	2016	US Army Corps of Engineers and **US Bureau of Reclamation (USBR)**	National	Encompassing all aspects of large wood designs, this guide covers their geomorphic, hydrological, and ecological considerations. The authors also discuss the risks involved, regulatory considerations, and monitoring.	✓	✓	✓	—
Stream Restoration Design	Guidebook	2007	NRCS	National	Written by a distinguished team of stream experts, this guide covers different stream design processes and channel configurations. Additional topics covered include permitting, stream hydrology, and impacts on sediment.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
A Handbook for Prioritizing Wetland and Stream Restoration and Protection Using Landscape Analysis Tools	Guidebook	2013	Environmental Law Institute	National	Focusing on site selection, this guide helps managers use landscape analysis tools to determine the best sites for stream restoration based on social, environmental, and economic metrics. The authors also discuss the regulatory hurdles involved in stream restoration as well as non-regulatory markets for ecosystem services.	—	✓	✓	—
Restoring Western Headwater Streams with Low-Tech Process-Based Methods	Guidebook	2013	American Rivers	Western United States	This guide explains the difference between low-tech process-based restoration and traditional stream restoration methods, describing lessons learned from past projects. The authors include case studies, benefits, and funding sources.	✓	—	✓	✓
Rock Weir Design Guidance	Guidebook	2016	USBR	National	Rock weirs encompass multiple stream restoration techniques, including J-hooks, cross vanes, and step pools. The authors provide design guidance and information about the hydrology and geomorphology of rock weirs.	✓	—	✓	—
Rock Ramp Design Guidelines	Guidebook	2007	USBR	Western United States	Rock ramps include numerous bank protection techniques such as rock pack and stone toe protection. The authors discuss issues related to fish passage, constructed step pools, and riprap sizing.	✓	✓	—	✓

GRAY INFRASTRUCTURE ALTERNATIVES

Stream restoration can be an alternative to gray infrastructure approaches that address riverine flooding (levee and dike systems) or urban runoff (stormwater drainage systems). The ability of a stream restoration project to replace or supplement these gray infrastructure approaches depends strongly on the project's location and whether it is designed to create the necessary outcomes. Certain environmental conditions may require gray infrastructure rather than stream restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of stream restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Stream restoration attenuates floods by dissipating water energy by reintroducing natural meanders back into the stream. Reductions in channel slope and increases in channel length allow for a stream to temporarily hold more water, preventing excess water from flooding surrounding areas. Restored banks are also better able to divert runoff into the ground, limiting the amount of water the stream must handle (Sholtes 2009).
- **Drought mitigation:** Stream restoration spreads out the peak flows of a stream, keeping water in the riverine system over a longer period of time. Restoration also increases connectivity between streams and wetlands, which store excess water that can be accessed during times of drought. Finally, restoration can facilitate groundwater recharge both in riparian areas and the hyporheic zone of the steam, preparing a region for drought (Ameli and Creed 2019).
- **Reduced wildfire risk:** Stream restoration promotes healthy and adequately hydrated vegetation around the stream, increasing fire resistance. Furthermore, restored streams keep the ground around the stream more moist than degraded streams, limiting fire spread. Certain stream restoration techniques, such as BDAs, create wetlands that can serve as a large firebreak (Pugh et al. 2022).
- **Carbon storage and sequestration:** While the amount of carbon sequestered because of stream restoration varies based on the geographic setting, a restored stream stores significantly more carbon than a degraded one. Increased riparian vegetation, large wood, and soil carbon are all carbon sinks enhanced by stream restoration. Stream restoration holds water for longer periods within the riverine system, promoting plant growth and higher carbon concentrations in the soil (Hinshaw and Wohl 2021).
- **Heat mitigation:** Stream restoration promotes the growth of riparian vegetation, which reduces air temperatures in the surrounding areas. Additionally, a vegetated canopy shields the water from the sun, reducing water temperature and thus mortality in aquatic species. This benefit is especially pronounced in urban streams, where heavily vegetated streams play a major role in mitigating the urban heat island effect (Abdi et al. 2020).

Social and Economic

- **Recreational opportunities:** Stream restoration makes streams a much more visual pleasing and safe site to visit, increasing recreational activities along the stream. Stream restoration paves the way for recreational activities such as hiking, birdwatching, and canoeing (Kondolf and Micheli 1995).
- **Reduced erosion:** Stream restoration diverts water away from eroding banks and toward the middle of the channel, reducing erosion. Stabilizing materials such as coir logs, stone-toe protection, and woody debris slow runoff as it descends the streambank, limiting erosion. Vegetation growth promoted by planting native species and live cuttings alters the local microclimate, resulting in conditions that support soil stability (Wynn, Mostaghimi and Alphin 2004).
- **Clean drinking water:** Stream restoration filters harmful pollutants and excess nutrients out of the stream, preventing it from entering larger rivers. Furthermore, when stream temperatures rise, water filtration plants often must apply additional treatment measures to the water, increasing the cost. However, since stream restoration lowers the water temperature, healthy streams can reduce water treatment expenses (Honey-Rosés et al. 2013).
- **Jobs:** Contractors will need to be hired to perform the restoration activities, stimulating the local economy.
- **Mental health and well-being:** Stream restoration enhances greenspace, boosting residents' mental health and psychological well-being.
- **Resilient fisheries:** Stream restoration increases both water quality and quantity, improving conditions for fish. More complex stream morphology allows for greater habitat diversity, providing nursery grounds for juvenile fish. Additionally, removing stream barriers facilitates fish passage, enhancing the longitudinal connectivity of the stream (Shirey et al. 2016).
- **Cultural values:** Streams and their inhabitants are important in a variety of cultures. Stream restoration can also be an opportunity to educate the public about the value role streams play in protecting water quality.

Ecological

- **Improved water quality:** Stream restoration improves water quality by lowering the amount of excess nutrients and sediments entering a stream. Streams are ecologically sensitive, meaning they cannot tolerate large fluxes of nutrients or sediments. Bank stabilization techniques guard the stream from nutrient and sediment runoff and in-stream rock structures limit channel erosion, improving water quality (Thompson et al. 2018). Stream restoration increases connectivity between the stream and its floodplain. Floodplain and riparian vegetation can trap excess nutrients, preventing them from flowing downstream. Furthermore, bank revegetation can prevent nutrients from entering the stream to begin with, as riparian vegetation is able to absorb excess nutrients (McMillan and Noe 2017). Stream restoration also reduces erosion, lowering the amount of sediment that enters a stream. This results in a lower concentration of suspended sediments in the stream, reducing the turbidity of the water and enhancing water quality (Siemion et al. 2016).

- **Enhanced biodiversity:** While stream restoration can increase biodiversity, increasing habitat diversity alone is not enough to restore biodiversity. Removing anthropogenic barriers in streams, limiting water extractions, reducing agricultural runoff, and removing invasive species are effective restoration strategies that can further increase biodiversity (Palmer et al. 2010).
- **Reduced runoff:** One of the primary goals of stream restoration is to reduce bank erosion, preventing excess sediment from entering the stream. Increased bends in the stream better catch excess sediment deposited downstream, reducing the amount of sediment impacting larger rivers (Kassa et al. 2023).
- **Supports wildlife:** Stream restoration creates a diversity of habitats, providing shelter for juvenile fish. This increases the species richness in the stream, with both species that prefer the open water and sheltered coves now able live in the same stream channel (Lorenz et al. 2013). Anthropogenic barriers in streams are major impediments to genetic diversity in fish species, with the barriers dividing populations into distinct subgroups. This results in genetic drift, where the subpopulations show less resemblance to each other over time. Removing these barriers restores interbreeding amongst the subpopulations, infusing new genes into the gene pool and strengthening the evolutionary capacity of the species (Raeymaekers et al. 2008).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the nature-based solutions strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about the barriers specific to stream restoration are included here.

- **Expense:** Some studies have shown that high stream restoration costs may not always be offset by the benefits provided, especially when gray infrastructure alternatives are possible (Kenney et al. 2012).
- **Capacity**
- **Public opinion:** Stream restoration projects that do not include sufficient stakeholder engagement and community buy-in are often less successful (Murphy et al. 2022)
- **Conflict with other land uses:** Form-based restoration is the most popular approach to stream restoration in the United States because all the work can be done within the stream channel, with no changes to the surrounding land uses. However, process-based restoration has seen greater success because it is better equipped to deal with the sources of stream degradation. This involves changing land use practices adjacent to the stream, such as farming or development, which has more economic downsides than form-based restoration (Hawley 2018).
- **Regulation**
- **Lack of effectiveness data:** Consistent monitoring of appropriate metrics that determine project success for river and stream restoration is rare (Bernhardt et al. 2005).

Ecological

- **Failure to understand and address ecological stressors:** Some common pitfalls in river and stream restoration that can cause a project not to perform as expected include creating habitat types outside a site's natural potential, not stabilizing habitat features, and restoring habitats that get overwhelmed by system drivers that were not addressed through the restoration (Beechie et al. 2010).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Trail Creek Forest Service Project	Gunnison National Forest, CO	US Department of Agriculture Forest Service, National Forest Foundation, American Rivers	Process-based restoration including installation of 32 BDAs, 12 sod speedbump structures, 18 woody material structures	0.5 miles	Not provided	1	Using process-based restoration to restore a stream that had become a simplified narrow channel with 1-to-2 ft bank incisions and to rewet valley-wide wetlands. The project aimed to slow water moving through the watershed, with goals of recharging the local aquifer, contributing to late season flows, increasing biodiversity, and decreasing drought impacts on downstream communities.	No	No
Stream Restoration of the Lake Julia Outfall (Reasonover Creek)	DuPont State Forest, NC	North Carolina Forest Service	A new stream channel was established and water control structures were installed using boulders and large logs. Trees were planted in a nearby floodplain forest	600 feet of stream	>$150,000	2	A segment of the creek was rerouted in the 1950s and, over time, had undercut a 30 ft, bare-soil embankment that was collapsing and adding excessive sediment into the stream. (Additional source.)	No	No

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Chilogatee Stream Restoration Project	Great Smoky Mountains National Park, TN	**National Park Service,** Tennessee Stream Mitigation Program	Establishing a new stream channel as well as recontouring other sections of the stream, in addition to planting native seeds and seedlings in riparian areas. Large boulders and logs were used to help reconstruct the stream channel.	4,600 linear feet	Not provided	Not provided	The stream had been degraded from riparian forest clearing, channel relocations, and unrestricted livestock access prior to the site's inclusion in the national park. The project goals were to restore natural stream morphology, connectivity of the stream to the floodplain, create healthy aquatic habitat, and reduce sediment input.	No	Adaptive management plan is located in this source document.

Bolding indicates DOI affiliates.

REFERENCES

Abbe, T., M. Hrachovec, and S. Winter. 2018. *Engineered Log Jams: Recent Developments in Their Design and Placement, with examples from the Pacific Northwest, U.S.A.* Amsterdam, Netherlands: Elsevier. https://naturaldes.com/wp-content/uploads/2018/11/Engineered-Log-Jams_Recent-Developments-in-Their-Design-and-Placement.pdf.

Abdi, R., T. Endreny, and D. Nowak. 2020. "A Model to Integrate Urban River Thermal Cooling in River Restoration." *Journal of Environmental Management* 258: 110023. https://doi.org/10.1016/j.jenvman.2019.110023.

Ameli, A. A., and I. F. Creed. 2019. "Does Wetland Location Matter When Managing Wetlands for Watershed-Scale Flood and Drought Resilience?" *Journal of the American Water Resources Association* 55(3): 529–42. https://doi.org/10.1111/1752-1688.12737.

Bailey, D. R., B. J. Dittbrenner, and K. P. Yocom. 2019. "Reintegrating the North American Beaver (Castor Canadensis) in the Urban Landscape." *WIREs Water* 6(1): e1323. https://doi.org/10.1002/wat2.1323.

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(3): 209–22. https://doi.org/10.1525/bio.2010.60.3.7.

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, et al. 2005. "Synthesizing U.S. River Restoration Efforts." *Science* 308(5722): 636–37. https://doi.org/10.1126/science.1109769.

Bernhardt, E. S., and M. A. Palmer. 2007. "Restoring Streams in an Urbanizing World." *Freshwater Biology* 52(4): 738–51. https://doi.org/10.1111/j.1365-2427.2006.01718.x.

Biron, P. M., T. Buffin-Bélanger, M. Larocque, G. Choné, C.-A. Cloutier, M.-A. Ouellet, S. Demers, T. Olsen, C. Desjarlais, and J. Eyquem. 2014. "Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience." *Environmental Management* 54(5): 1056–73. https://doi.org/10.1007/s00267-014-0366-z.

Bischetti, G. B., E. A. Chiaradia, V. D'Agostino, and T. Simonato. 2010. "Quantifying the Effect of Brush Layering on Slope Stability." *Ecological Engineering* 36(3): 258–64. https://doi.org/10.1016/j.ecoleng.2009.03.019.

Craig, L. S., M. A. Palmer, D. C. Richardson, S. Filoso, E. S. Bernhardt, B. P. Bledsoe, M. W. Doyle, et al. 2008. "Stream Restoration Strategies for Reducing River Nitrogen Loads." *Frontiers in Ecology and the Environment* 6(10): 529–38. https://doi.org/10.1890/070080.

Doll, B. A., G. L. Grabow, K. R. Hall, J. Halley, W. A. Harman, G. D. Jennings, and D. E. Wise. 2003. *Stream Restoration: A Natural Channel Design Handbook*. Raleigh and Morehead City, NC: North Carolina State University and North Carolina Sea Grant. https://repository.library.noaa.gov/view/noaa/36133.

EPA. 2013. *Rivers & Streams*. Washington, DC: United States Environmental Protection Agency. https://archive.epa.gov/water/archive/web/html/index-17.html.

Gordon, R. P., L. K. Lautz, and T. L. Daniluk. 2013. "Spatial Patterns of Hyporheic Exchange and Biogeochemical Cycling around Cross-Vane Restoration Structures: Implications for Stream Restoration Design." *Water Resources Research* 49(4): 2040–55. https://doi.org/10.1002/wrcr.20185.

Hawley, R. J. 2018. “Making Stream Restoration More Sustainable: A Geomorphically, Ecologically, and Socioeconomically Principled Approach to Bridge the Practice with the Science.” *Bioscience* 68(7): 517–28. https://doi.org/10.1093/biosci/biy048.

Higgs, S. 2002. *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. Washington, DC: American Rivers. https://www.americanrivers.org/wp-content/uploads/2016/05/EcologyOfDamRemovalcf24.pdf

Hinshaw, S., and E. Wohl. 2021. “Quantitatively Estimating Carbon Sequestration Potential in Soil and Large Wood in the Context of River Restoration.” *Frontiers in Earth Science* 9. https://www.frontiersin.org/articles/10.3389/feart.2021.708895.

Honey-Rosés, J., V. Acuña, M. Bardina, N. Brozović, R. Marcé, A. Munné, S. Sabater, et al. 2013. “Examining the Demand for Ecosystem Services: The Value of Stream Restoration for Drinking Water Treatment Managers in the Llobregat River, Spain.” *Ecological Economics* 90: 196–205. https://doi.org/10.1016/j.ecolecon.2013.03.019.

Kassa, K., C. Castro-Bolinaga, L. Guertault, G. A. Fox, P. Russell, and E. D. Brown. 2023. “Quantifying the Impact of Model Selection When Examining Bank Retreat and Sediment Transport in Stream Restoration.” *Water* 15(8): 1448. https://doi.org/10.3390/w15081448.

Kenney, M. A., P. R. Wilcock, B. F. Hobbs, N. E. Flores, and D. C. Martínez. 2012. “Is Urban Stream Restoration Worth It?” *Journal of the American Water Resources Association* 48(3): 603–15. https://doi.org/10.1111/j.1752-1688.2011.00635.x.

Kondolf, G. M., and E. R. Micheli. 1995. “Evaluating Stream Restoration Projects.” *Environmental Management* 19(1): 1–15. https://doi.org/10.1007/BF02471999.

Lorenz, A. W., S. Stoll, A. Sundermann, and P. Haase. 2013. “Do Adult and YOY Fish Benefit from River Restoration Measures?” *Ecological Engineering* 61(A): 174–81. https://doi.org/10.1016/j.ecoleng.2013.09.027.

MCDEP. 2023. *Stream Restoration*. Montgomery County, MD: Department of Environmental Protection. https://www.montgomerycountymd.gov/water/restoration/streams.html.

McMillan, S. K., and G. B. Noe. 2017. “Increasing Floodplain Connectivity Through Urban Stream Restoration Increases Nutrient and Sediment Retention.” *Ecological Engineering* 108(A): 284–95. https://doi.org/10.1016/j.ecoleng.2017.08.006.

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: 1681–92. https://doi.org/10.1007/s12665-009-0150-1.

Murphy, B. M., K. L. Russell, C. C. Stillwell, R. Hawley, M. Scoggins, K. G. Hopkins, M. J. Burns, K. T. Taniguchi-Quan, K. H. Macneale, and R. F. Smith. 2022. “Closing the Gap on Wicked Urban Stream Restoration Problems: A Framework to Integrate Ccience and Community Values. *Freshwater Science* 41(3): 521–31. https://doi.org/10.1086/721134.

NRCS. 2007. “Stream Restoration Design Process.” In *Stream Restoration Design National Engineering Handbook,* edited by J. M. Bernard, J. Fripp, and K.

Robinson, 4-a–4-26. Washington, DC: United States Department of Agriculture National Resources Conservation Center. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17780.wba.

NRCS. 2012. *Stream Restoration Planning and Design Field Guide*. Washington, DC: United States Department of Agriculture National Resources Conservation Service. https://efotg.sc.egov.usda.gov/references/public/WV/StreamRestorationPlanningWorkshopFieldGuide_revisedJuly2012_pp1-71.pdf.

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(s1): 205–22. https://doi.org/10.1111/j.1365-2427.2009.02372.x.

Pugh, B. E., M. Colley, S. J. Dugdale, P. Edwards, R. Flitcroft, A. Holz, M. Johnson, et al. 2022. "A Possible Role for River Restoration Enhancing Biodiversity through Interaction with Wildfire." *Global Ecology and Biogeography* 31(10): 1990–2004. https://doi.org/10.1111/geb.13555.

Purcell, A. H., C. Friedrich, and V. H. Resh. 2002. "An Assessment of a Small Urban Stream Restoration Project in Northern California." *Restoration Ecology* 10(4): 685–94. https://doi.org/10.1046/j.1526-100X.2002.01049.x.

Raeymaekers, J. A. M., G. E. Maes, S. Geldof, I. Hontis, K. Nackaerts, and F. A. M. Volckaert. 2008. "Modeling Genetic Connectivity in Sticklebacks as a Guideline for River Restoration." *Evolutionary Applications* 1(3): 475–88. https://doi.org/10.1111/j.1752-4571.2008.00019.x.

Rinaldi, M., and P. A. Johnson. 1997. "Characterization of Stream Meanders for Stream Restoration." *Journal of Hydraulic Engineering* 123(6): 567–70. https://doi.org/10.1061/(ASCE)0733-9429(1997)123:6(567).

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 Watersheds." *North American Journal of Fisheries Management* 22(1): 1–20. https://doi.org/10.1577/1548-8675(2002)022<0001:AROSRT>2.0.CO;2.

Selvakumar, A., T. P. O'Connor, and S. D. Struck. 2010. "Role of Stream Restoration on Improving Benthic Macroinvertebrates and In-Stream Water Quality in an Urban Watershed: Case Study." *Journal of Environmental Engineering* 136(1): 127–39. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000116.

Shields Jr., F D., S. S. Knight, and C. M. Cooper. 1998. "Addition of Spurs to Stone Toe Protection for Warmwater Fish Habitat Rehabilitation1." *Journal of the American Water Resources Association* 34(6): 1427–36. https://doi.org/10.1111/j.1752-1688.1998.tb05442.x.

Shirey, P. D., M. A. Brueseke, J. B. Kenny, and G. A. Lamberti. 2016. "Long-Term Fish Community Response to a Reach-Scale Stream Restoration." *Ecology and Society* 21(3). https://www.jstor.org/stable/26269955.

Sholtes, J. 2009. *Hydraulic Analysis of Stream Restoration on Flood Wave Propagation*. Chapel Hill, NC: University of North Carolina. https://www.proquest.com/docview/304959327/abstract/D2BD754551184D09PQ/1.

Siemion, J., M. R. McHale, and W. D. Davis. 2016. *Suspended-Sediment and Turbidity Responses to Sediment and Turbidity Reduction Projects in the Beaver Kill, Stony Clove Creek, and Warner Creek Watersheds, New York, 2010–14*. Reston, VA: United States Geological Survey. https://doi.org/10.3133/sir20165157.

Sulpizio, J. 2020. "Slow the Spread of Aquatic Invasive Species." *Pennsylvania State University Extension,* April 9, 2020. https://extension.psu.edu/slow-the-spread-of-aquatic-invasive-species.

Sweeney, E., P. Womble, J. B. Wilkinson, R. Kihslinger, and J. Amsalem. 2013. *A Handbook Prioritizing Wetland and Stream Restoration and Protection Using Landscape Analysis Tools*. Washington, DC: Environmental Law Institute. https://www.eli.org/sites/default/files/eli-pubs/d23_09.pdf.

Thomas-Blate, J. 2023. "Dam Removals Continue Across the U.S. in 2022." *American Rivers,* February 14, 2023. https://www.americanrivers.org/2023/02/dam-removals-continue-across-the-u-s-in-2022/.

Thompson, J., C. E. Pelc, W. R. Brogan, and T. E. Jordan. 2018. "The Multiscale Effects of Stream Restoration on Water Quality." *Ecological Engineering* 124: 7–18. https://doi.org/10.1016/j.ecoleng.2018.09.016.

Toran, L., B. Hughes, J. Nyquist, and R. Ryan. 2012. "Using Hydrogeophysics to Monitor Change in Hyporheic Flow around Stream Restoration Structures." *Environmental & Engineering Geoscience* 18(1): 83–97. https://doi.org/10.2113/gseegeosci.18.1.83.

Unser, C., C. Litton, and T. Sylva. 2009. *Use of Native Plants and Coir Fiber Logs for Nitrogen Uptake in Waimānalo Stream*. Manoa, HI: University of Hawaii. https://www.researchgate.net/publication/242541894_Use_of_Native_Plants_and_Coir_Fiber_Logs_for_Nitrogen_Uptake_in.

Vietz, G. J., I. D. Rutherfurd, T. D. Fletcher, and C. J. Walsh. 2016. "Thinking Outside the Channel: Challenges and Opportunities for Protection and Restoration of Stream Morphology in Urbanizing Catchments." *Landscape and Urban Planning* 145: 34–44. https://doi.org/10.1016/j.landurbplan.2015.09.004.

Wohl, E., S. N. Lane, and A. C. Wilcox. 2015. "The Science and Practice of River Restoration." *Water Resources Research* 51(8): 5974–97. https://doi.org/10.1002/2014WR016874.

USGS. 2018. "Dissolved Oxygen and Water." *United States Geological Survey Water Science School,* June 5, 2018. https://www.usgs.gov/special-topics/water-science-school/science/dissolved-oxygen-and-water#:~:text=Rapidly%20moving%20water%2C%20such%20as,oxygen%20as%20organic%20matter%20decays.

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