Riverine Habitats
24. Riverine Connectivity Restoration

DEFINITION

A *riverine system* is a watershed-scale network of integrated aquatic habitats and hydrological processes (McCluney et al. 2014). A riverine system consists of the area drained by a primary river and its tributaries. A riverine system functions as both a habitat and migration corridor, with connectivity projects enhancing the sustainability of both (Seliger and Zeiringer 2018). Riverine connectivity is concerned with providing longitudinal access between points along the main channel of a river. A well-connected river sustains natural riverine processes, including the unimpeded movement of fish, sediment, and nutrients to points further up- and downstream (MDBA n.d.). This reduces habitat fragmentation, flow alterations, and conditions conducive to invasive species (Arboleya et al. 2021). Riverine connectivity is blocked by numerous anthropogenic alterations to rivers, including weirs, dams, culverts, fords, sluice gates, and roads (Soton 2018). Restoring riverine connectivity as a nature-based solution (NBS) involves removing these physical barriers, eliminating hypoxic zones, redesigning road stream crossings, and reintroducing natural meanders back into river morphology (Woolsey et al. 2007).

TECHNICAL APPROACH

The following strategies are frequently used to restore riverine connectivity:

- **Dam removal:** Dams alter nutrient cycling, impact the deposition of sediment, reduce flood frequency, and limit the range of migratory aquatic species, all of which deprive rivers of their ecological health (Bednarek 2001). Once a dam is removed (Figure 1), river flow will increase, decreasing temperature and increasing dissolved oxygen levels (Higgs 2002). While these changes may have a short-term negative impact on the ecosystem as a result of the large flux in conditions immediately afterward, they are far outweighed by the long-term benefits. Fish migration, sediment deposition, and a decrease in eutrophication help nurture the river back to its natural state (Higgs 2002). Dam removal techniques vary. Often, water is diverted so that the dam can be deconstructed “in the dry.” Alternatively, dams can be deconstructed “in the wet,” where the dam is slowly lowered over an extended duration of time to allow the riverine system time to adjust to the new water flow (American Rivers 2023).
- **Invasive species removal:** Invasive species can have profound impacts on the hydrology of a riverine system. Invasive species generally use more water than native ones, reducing river flow and exacerbating drought (Jansson et al. 2007). Frequent invasive species in American rivers include zebra mussels (*Dreissena polymorpha*), lampreys (*Petromyzontiformes spp.*), purple loosestrife (*Lythrum salicaria*) and nutrias (*Myocastor coypus*). While control methods vary depending on the target species, common strategies involve biological, chemical, mechanical, physical, and cultural approaches (USDA 2023).

Figure 24.1 Dam removal on Octoraro Creek, MD

Photo courtesy US Fish and Wildlife Service

- **Replacing culverts:** Culverts block migration of fish and aquatic species when they are too small, steep, or at a higher elevation than the water directly downstream (NOAA 2022). Existing culverts can be replaced with larger, less-steep ones to address these issues (Figure 2). Culverts must be large enough to transport fish and sediments downriver while still accommodating the existing road infrastructure passing over the stream (Wellman et al. 2000).
- **Redesigning road stream crossings:** Like culverts, many road stream crossings are poorly designed and hinder the movement of wildlife throughout the length of a river or creek. Poorly designed road stream crossings include vertical barriers, low-water crossings, unnatural bed substrates, high–water velocity crossings, clogged crossings, and crossings that cause bed scour. These can be replaced with well-designed crossings that better account for local geomorphology. Characteristics of well-designed crossings include comparable water depth and flow to nearby stream conditions, sufficient size for high flows, retaining the natural stream channel and substrates and spanning the entire stream (Gring 2021).
- **Eliminating hypoxic zones:** *Hypoxia* refers to low levels of dissolved oxygen in aquatic habitats, making hypoxic zones virtually devoid of aquatic life (NOAA 2023). Hypoxic zones often occur in river deltas or near the mouths of major rivers because nutrient pollution (primarily nitrogen and phosphorus) from the whole riverine system

Figure 24.2 Fish-friendly culvert in Anchorage, AK

Photo courtesy US Fish and Wildlife Service Alaska Region

accumulates here (Mitsch and Day 2006). This blocks aquatic organisms from entering and exiting the riverine system (NOAA 2023). Numerous strategies can be used to mitigate nutrient pollution and thus reduce hypoxic zones. These include planting wetlands near agricultural areas, installing riparian buffers, and changing agricultural practices (Mitsch and Day 2006).

- **Reintroducing natural meanders:** *Meanders*, where the main channel of a river migrates through its floodplain in a curved shape, are frequently straightened to make rivers more navigable for large ships (NWRM 2013). However, this reduces the diversity of habitats within a river and makes portions of the river unnavigable for some species (Pess et al. 2006). Heavy equipment can be used to change the local topography and reconnect the main channel with cut-off meanders in the floodplain, reducing the water velocity of the river (NWRM 2013).
- **Fish passage structures:** In cases where removing dams or weirs is not possible, fish passage structures can still enhance riverine connectivity for migratory fish (Figure 3). Examples of fish passage structures include bypass channels, fish locks, fish ladders, and fish lifts (Beechie and Roni 2012). Many of the designs combine green and grey infrastructure and are placed adjacent to a dam or weir (Beechie and Roni 2012).

OPERATIONS AND MAINTENANCE

Operations and maintenance will differ for various riverine connectivity project types, but these activities can include intermittent invasive species removal efforts, removing blockages from culverts and stream crossing structures, and maintaining fish passage structures as they age.

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Dams that are no longer in use:** Dams that are no longer functioning for their original purpose are often targeted for removal. Since the dam is no longer generating revenue, maintenance costs begin to pile up. Often, dams are removed when removal is deemed cheaper than maintenance (American Rivers 2023).
- ✓ **Ample space between infrastructure and the river:** Having a buffer zone to allow for changes in the hydrological regime of the river is ideal. Having extra room along the riverbank allows for the incorporation of natural meanders and diverse aquatic habitats into a project.

Figure 24.3 Fish ladder in Vermont

Photo courtesy US Fish and Wildlife Service Northeast Region

- ✓ **Near a restored wetlands or floodplains site:** Pairing wetland restoration or floodplain reconnection with a riverine connectivity allows benefits from the adjacent ecosystem to help the project. For example, building side channels for salmon spawning grounds as a part of a floodplain reconnection project multiplies the benefits of building a fish passage structure in a riverine connectivity project.
- ✓ **Near the mouth of the river:** Removing barriers to riverine connectivity near the outlet of a river will have a greater impact on all upstream tributaries.
- ✓ **Overpasses for smaller rural roads and trails:** Despite receiving little traffic, rural road and trail overpasses pose significant barriers to riverine connectivity. These overpasses are generally small, meaning that renovating or replacing them will be less expensive (Gring 2021). Many of these routes are seldom-traveled, resulting in minimal economic disruptions while realizing large benefits for wildlife.
- ✗ **Areas prone to erosion:** Riverbed erosion deprives the area of sediment needed sustain a healthy river. Unless the source of erosion is being addressed as a part of the project, then eroded areas should be avoided (Rhode et al. 2006).
- ✗ **Densely populated urban areas:** The lack of open space and highly modified nature of urban rivers makes it difficult to implement river restoration in urban areas. However, urban rivers can still use riverine connectivity techniques as a part of a green-gray approach (Guimarães et al. 2021).
- ✗ **Flood-prone regions:** Removing gray infrastructure may increase flood risk in areas with high amounts of development in the floodplain. For example, dam and levee removal as a part of riverine connectivity can result in flooding downstream (Guimarães et al. 2021).
- ✗ **Areas with frequent commercial shipping:** Locks, which pose a major barrier to riverine connectivity, are vital for commercial ships traversing rivers with steep gradients. Furthermore, vessel-induced waves from large ships can cause habitat loss and riverbank erosion (Liedermann et al. 2014). Thus, rivers that receive heavy commercial ship travel are generally not suitable for a riverine connectivity project.

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 and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats	Guidebook	2012	Philip Roni and Tim Beechie	National	This comprehensive resource provides in-depth information for developing watershed restoration projects. Topics covered include the human dimensions of riverine connectivity, identifying restoration needs, developing and implementing projects, and project monitoring and evaluation.	✓	✓	✓	—
Renewing Our Rivers: Stream Corridor Restoration in Dryland Regions	Guidebook	2021	Mark K. Briggs and Waite R. Osterkamp	Focus on arid regions but most of the information is more broadly applicable	With a special emphasis on the role climate change plays in shaping riverine systems, this resource provides information on how to plan and enact a river restoration project. With numerous case studies of successful riverine connectivity projects, the guidebook provides insights into designing an effective plan.	✓	✓	✓	✓
Iowa's River Restoration Toolbox	Website	Not provided	Iowa Department of Natural Resources	Focus on Iowa but most of the information is more broadly applicable	Comprised of numerous detailed diagrams, this tool provides technical information for assessing a waterbody and determining the appropriate restoration technique. In depth information is also given about contractor relations and project execution.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
National River Restoration Scientific Synthesis (NRRSS) Database	Database	2007	American Rivers, University of Michigan, University of Maryland	National	Compiled by scientists, the NRRSS database contains information about more than 37,000 river restoration projects in the United States It also collects scientific papers on river connectivity that originated from information found in the database.	✓	—	—	✓
Society for Ecological Restoration (SER) Project Database	Database	2023	Society for Ecological Restoration	Global	Comprised of projects from around the world, the SER database is a vast repository of ecological knowledge. To find projects specifically related to riverine connectivity, filters can narrow down results by ecosystem and biome type.	—	—	—	✓
River Restoration Science & Socio-Economic Resources	Website	2023	American Rivers	National	The website provides a diversity of tools highlighting the best practices for riverine connectivity restoration. A special emphasis is placed on dam removal, floodplain restoration, and the economics of river restoration.	✓	✓	✓	✓
River Barrier Prioritizations Database	Website	2023	American Rivers	National	This is an inventory of barriers to aquatic connectivity in the United States. The database also prioritizes structures whose removal would be particularly ecologically beneficial.	—	✓	—	✓

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Low-Tech Process-Based Restoration of Riverscapes Design Manual	Guidebook	2019	Utah State University Restoration Consortium	National	The authors show how river restoration centers around restoring the hydrological processes that make a riverine system successful. The guide focuses on low-tech and cost-efficient solutions, including beaver dam analogs and assisted wood accumulation.	✓	—	✓	✓
USA Dam Removal Experience and Planning	Guidebook	2021	US Bureau of Reclamation	National	This document compiles knowledge about dam removal design, planning, and monitoring. This resource also provides case studies of successful dam removal projects and their associated ecological benefits.	✓	✓	✓	✓

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Well-connected rivers can adequately distribute excess water throughout the riverine network during peak flow times, given a functioning floodplain (see floodplain reconnection strategy) (Trigg et al. 2013).
- **Drought mitigation:** Rivers are better able to respond to droughts when they are connected. During droughts, rivers may temporarily dry up in certain locations, so connectivity allows aquatic animals to move along the length of a river to interbreed with other populations (Palmer and Ruhi 2019). Additionally, riverine connectivity increases the frequency of the river flow and enhances the hydrological exchange with

the hyporheic zone, where river water percolates into groundwater aquifers, thus better recharging aquifers that can sustain communities through droughts (Song et al. 2018).

- **Sea level rise adaptation and resilience:** Connected rivers deliver sediment to the mouth of the river, helping the area around the river delta keep pace with sea level rise (Phillips and Slattery 2006). However, natural sediment deposition has been disrupted by anthropogenic alterations to rivers, especially dams, which trap sediment upstream (Topping et al. 2000). Restoring riverine connectivity by removing dams and other barriers allows sediment deposition to resume (Bednarek 2001).
- **Carbon storage and sequestration:** River channels can store more carbon per acre than upland ecosystems because of the large amount of soil organic carbon and downed wood (Wohl 2020).

Social and Economic

- **Increased property values:** Property values in areas near a restored river have been found to significantly increase following dam removal (Lewis et al. 2008).
- **Recreational opportunities:** Riverine connectivity provides an opportunity for additional parkland along the river, boosting tourism and recreation opportunities.
- **Clean drinking water:** Riverine connectivity enhances the natural purification qualities of a river, resulting in cleaner drinking water and less anthropogenic drinking water treatment (Chen et al. 2022).
- **Jobs:** Workers will need to be hired to perform the riverine connectivity projects, boosting the local economy.
- **Mental health and well-being:** Restored rivers can serve as greenspace, which strengthens residents' mental health.
- **Resilient fisheries:** Restoring local fisheries is one of the most common objectives cited by entities completing riverine connectivity projects. Riverine connectivity allows migrating species to return to their spawning grounds and increases genetic diversity within populations (Beechie et al. 2008). There are many varieties of fish passage structures that aid fish's longitudinal connectivity throughout a river basin (Beechie and Roni 2012).
- **Cultural values:** Riverine connectivity can increase local awareness of and pride in aquatic ecosystems. Aquatic species and ecosystem processes restored via riverine connectivity are integral to traditions of many Indigenous communities.

Ecological

- **Improved water quality:** Disruption to river flow hinders natural riverine processes that purify water. Connected rivers foster healthier ecosystems that are better able to tolerate and neutralize pollutants (Zaidel et al. 2021). By reducing erosion and other sources of excess sediments, riverine connectivity also reduces turbidity and increases water clarity (Palmer et al. 2005).

- **Enhanced biodiversity:** Enhanced riverine connectivity has been shown to increase both species richness and species diversity. This can be attributed to greater organism movement, less pollutants and eutrophication, and higher dissolved oxygen levels in well-connected rivers (Cantonati et al. 2020).
- **Enhanced genetic diversity:** Dams create isolated populations of fish who can only interbreed among themselves, reducing the gene pool. Once a river is reconnected, isolated fish populations can intermix, resulting in a fresh infusion of genes and increasing the health of the population (Piotrowski 2021).
- **Supports wildlife:** Riverine connectivity can allow for more exchanges with the surrounding floodplain (lateral connectivity) (see floodplain reconnection strategy) and a greater diversity of habitats surrounding the riverine ecosystem, from the groundwater to the atmosphere (vertical connectivity) (MN DNR 2023).
- **Increased primary productivity:** Riverine ecosystems thrive on variable water flows, which are stabilized by blockages in the river such as dams. Restoring flow variability eliminates numerous competitively dominant species, enhancing the whole ecosystem and increasing primary productivity (Palmer et al. 2005).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the NBS strategies; these are described in more detail in the Section 1 of the Roadmap. Additional notes about the barriers specific to riverine connectivity are included here.

- **Expense:** Because of the large scale of infrastructure blocking rivers, costs to restore riverine connectivity are high. The Elwha Dam removal project, one of the largest in the United States, cost $325 million (Cho 2011). Even smaller removals can still be pricey. The removal of a small dam system that once powered textile mills along the Patapsco River in Maryland cost $2.7 million (Hirsch 2012).
- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** There are currently 2,210 hydroelectric dams in the United States, producing 6.3% of the nation's electricity (Cho 2011, DOE 2023). Reliance on hydropower is even more pronounced in some areas of the country. The Bonneville Power Administration, which only produces electricity via hydropower, provides 28% of the Pacific Northwest's electricity (BPA 2023). Dam removal also significantly reduces the amount of water available in reservoirs, although free-flowing rivers are more effective at storing water in underground aquifers (Poff and Hart 2002). Thus, it is not economically viable to remove dams in many instances.
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Impact on agricultural practices:** Given that remediating hypoxic zones is a way to improve riverine connectivity, this solution is reliant on farmers reducing their nutrient pollution (Mitsch and Day 2006). Transitioning to more sustainable practices to reduce nutrient runoff may economically hurt some agricultural facilities (EPA 2022).

Community

- **Change in local flood regime:** Flood-control dams are built to alter the seasonal flow patterns of rivers, reducing peak flows and mitigating floods. When the dam is removed the natural flood regime will gradually reemerge, resulting in more frequent floods (Poff and Hart 2002). Downstream development previously protected by the dam will now become flood-prone.
- **Jurisdictional overlaps:** Rivers are common physical boundaries that divide political entities. As a result, opposite banks of a river are often subject to different jurisdictional authorities. This makes it difficult to coordinate riverine connectivity projects.

Ecological

- **Managing sediment built up behind dams:** While dam removal helps sediment transportation in the long term, in the short term, dam removal can stir up excess sediments and transport them downriver. These sediments are often laden with toxic chemicals, greatly damaging downriver habitat (Cho 2011).
- **Rapid shifts in biogeochemical cycling:** Similar to sediment transport, removing river barriers temporarily disrupts biogeochemical cycling while restoring it in the long term. Large quantities of nitrogen and phosphorus that accumulated behind barriers are suddenly released, creating a surplus of nitrogen and phosphorus downriver (Hart et al. 2002).
- **Invasive species proliferation:** Many nascent aquatic invasive species have their range limited by artificial river barriers (Habel et al. 2020). However, once these barriers are removed, the invasive species can travel to previously protected habitats, outcompeting native species.

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Potomac Headwaters Fish Passage Restoration Project	Potomac headwaters of the Chesapeake Bay (Maryland, Virginia, West Virginia)	**US Fish and Wildlife Service (USFWS)**	Culvert replacement, redesigned road stream crossings, fish passage structures	195 stream miles reconnected	1.15 million	Ongoing, began 2022	The project is removing 17 barriers to fish passage along the tributaries of the Potomac River. This includes culvert and low bridge replacements, dam removal, and installing fish ladders.	Inland flooding	No
Sabattus River Connectivity Project	Lisbon, Maine	**USFWS,** Maine Department of Natural Resources, Town of Lisbon, Atlantic Salmon Federation	Dam removal	9 river miles reconnected	650,000	3	Contractors removed two failed dams that blocked fish passage and posed a flood risk to the town of Lisbon.	Inland flooding	Removing the dams allowed for the Sabattus River to better manage stormwater runoff.
Good River Connectivity Project	Gustavus, Alaska	**USFWS,** Alaska Department of Natural Resources, City of Gustavus, National Oceanic and Atmospheric Administration (NOAA), National Wildlife Federation	Culvert replacement, redesigning road stream crossing	6 stream miles reconnected	1.76 million	5	To restore river connectivity, culvert crossings on the Good River were replaced with bridges that allowed fish to pass.	No	Isostatic rebound, where land rises after an ice sheet retreats, caused an imbalance in elevation that blocked fish from passing.
Upper Clark Fork Fish Passage Project	Upper Clark Fork River, Montana	**USFWS,** US Department of Agriculture Forest Service, Montana Department of Natural Resources, Trout Unlimited	Dam removal, fish passage structures	55 river miles reconnected	250,000	1	The team used a plethora of fish passage structures to help fish navigate barriers on the Upper Clark Fork River.	No	Because many of the structures removed were historic, the permitting process took extra time and drive.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Moose Creek Connectivity Project	Moose Creek, Alaska	**National Park Service (NPS), USFWS,** NOAA, Chickaloon Native Village	Reintroducing natural meanders, weir removal, logjam installation	5 creek miles reconnected	Not provided	2	Managers removed weirs, reintroduced natural meanders to slow water flow, and installed logjams to help restore the natural hydrology of Moose Creek.	No	The team used historical railroad maps to discover the natural flow of the creek before it was altered.
Bluebird Dam Removal Project	Rocky Mountain National Park, Colorado	**NPS, Reclamation,** US Army Corps of Engineers (USACE)	Dam removal, vegetation planted	17 acres	1.3 million	2	After the catastrophic failure of another dam in Rocky Mountain National Park, the Bluebird Dam was inspected and found to be structurally unsound. The dam was removed and native vegetation was replanted in the former reservoir.	Inland flooding	To avoid adverse impacts to the native flora and fauna, multiple helicopters were used to transport rubble away from the site.
Carmel River Restoration Project	Carmel River, California	**Bureau of Land Management (BLM), USFWS,** NOAA, USACE, California State Coastal Conservancy	Dam removal, revegetation, boulder installation, off channel creation	25 river miles reconnected	84 million	3	After sediment buildup, nutrient pollution, and flooding caused by the San Clemente Dam degraded the Carmel River, officials decided to remove this large dam.	Inland flooding	Because of the severe sediment buildup behind the dam, engineers decided to reroute the river and plug the sediment before deconstructing the dam.

Name and Link	Location	Leading Organizations	Techniques Used	Size	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Neuse River Restoration Project	Neuse River, North Carolina	**USFWS,** US Environmental Protection Agency, NC Department of Environment and Natural Resources, USACE, NC Coastal Federation	Dam removal	1,000 miles of river and tributaries reopened	Not provided	20	Beginning 1997 and ending in 2017, six dams along the Neuse River were removed. While most dams were built to produce hydropower, drought and flood risk made upkeep impractical.	Inland flooding	By viewing river connectivity at the large scale of the total Neuse River Basin, each successive dam removal project was able to amplify the benefits of the previous one.

Bolding indicates DOI affiliates.

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