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Measures to safeguard and restore river connectivity

Michele Thieme[a], **Kim Birnie-Gauvin**[b], **Jeffrey J. Opperman**[c], **Paul A. Franklin**[d], **Holly Richter**[e], **Lee Baumgartner**[f], **Nathan Ning**[g], **An Vi Vu**[h], **Kerry Brink**[i], **Michael Sakala**[j], **Gordon C. O'Brien**[k], **Robin Petersen**[l], **Pakkasem Tongchai**[m], **and Steven J. Cooke**[n]

[a]World Wildlife Fund, 1250 24th Street, NW, Washington, DC, USA; [b]Freshwater Fisheries and Ecology Department, National Institute of Aquatic Resources, Technical University of Denmark, Silkeborg, Denmark; [c]World Wildlife Fund, Washington, DC, USA; [d]National Institute of Water and Atmospheric Research Hamilton, Hamilton, New Zealand; [e]Resilient Rivers LLC, Hereford, AZ, USA; [f]Gubali Institute, Charles Sturt University, Albury, NSW, Australia; [g]Gubali Institute, Charles Sturt University, Albury, NSW, Australia; [h]Research Institute of Aquaculture No. 2, Gubali Institute, Charles Sturt University, Ho Chi Minh City, VN, Albury, NSW, Australia; [i]WWF-Netherlands, Zeist, The Netherlands; [j]World Wide Fund for Nature Zambia, Lusaka, Zambia; [k]University of Mpumalanga, Mbombela, Mpumalanga, South Africa; [l]SANParks, Pretoria, South Africa; [m]IUCN Thai Country Program, Bangkok, Thailand; [n]Department of Biology, Carleton University, Ottawa, ON, Canada

Corresponding author: **Michele Thieme** (email: michele.thieme@wwfus.org)

Abstract

Freshwater connectivity and the associated flow regime are critical components of the health of freshwater ecosystems. When freshwater ecosystems are fragmented, the movements and flows of species, nutrients, sediments, and water are altered, changing the natural dynamics of freshwater ecosystems. The consequences of these changes include declines and loss of freshwater species populations and freshwater ecosystems, and alterations in the delivery of certain ecosystem services, such as fisheries, buffering of flood events, healthy deltas, recreational and cultural values, and others. Measures exist that can maintain and restore connectivity or mitigate against its loss in the face of constructed barriers or other habitat alterations. These measures include system-scale planning for energy and water resources that includes options for limiting loss of freshwater connectivity; putting in place protections for keeping critically important freshwater habitats connected; mitigating impacts on freshwater ecosystems via barrier design, fish passage, or implementation of environmental flows; and restoring freshwaters via barrier removal and reconnection of rivers, wetlands, and floodplains and via active management of groundwater recharge. We present case studies of measures applied in Europe, Asia, Africa, and the Americas and reflect on the next generation of innovation needed to further enhance and advance the implementation of restoration and protection and the mitigation of freshwater connectivity impacts.

Key words: freshwater, connectivity, biodiversity, restoration, protection

Introduction

Freshwater connectivity is fundamental for healthy land and riverscapes and for many of the services that they provide to humanity. These services include fisheries production, water regulation (i.e., groundwater recharge and buffering from flood events), nutrient and sediment transport to downstream floodplains, fields, and deltas, and recreational and cultural values (Durance et al. 2016). The ability of freshwater ecosystems to sustain biodiversity and deliver many ecosystem services is governed by the degree to which their natural flow regime and connectivity are maintained. River or fluvial connectivity extends in four dimensions: longitudinally (upstream and downstream in the river channel, including to estuarine and ocean systems), laterally (between the main channel, floodplain, and riparian areas), vertically (between groundwater, river, and atmosphere), and temporally (natural flows that include seasonal variations) (Ward 1989). Some hydrologic processes, such as the movement of groundwater through an aquifer, are three-dimensional in nature. Alterations in any of the four dimensions can affect fluvial processes and functions that span the abiotic and biotic realms.

Fluvial connectivity has been significantly affected around the world, with over two-thirds of long (>1000 km) rivers no longer considered free-flowing. Similarly, more than 1.2 million barriers, nearly 70% of which are less than 2 m in height, are fragmenting Europe's rivers (Belletti et al. 2020), and hundreds of barriers fragment the Lower Mekong Basin (Baumgartner et al. 2021). Despite widespread recognition of the role that river systems play in providing ecological connectivity and functionality across fluvial landscapes (Fausch et al. 2002), existing policy mechanisms and measurements of the health of rivers and watersheds often fail to include connectivity measures. Many governments focus their monitoring of freshwater ecosystems on water quality measures—with measurements and metrics of the status of environmental flows and fluvial connectivity only having been introduced in recent decades (Harwood et al. 2018), if at all. One recent example is the commitment by the European Union to restore 25,000 km of river under its Biodiversity Strategy 2030 (European Commission 2020).

The issue

A diverse range of species depend on freshwater connectivity within and between river reaches, floodplain habitats, wetlands, lakes, and estuaries, for foraging, reproduction, or seeking refuge (Lucas et al. 2001; McIntyre et al. 2016). A classic example is the outmigration of salmon smolts from rivers to the ocean and their subsequent return as adults to spawn, but the range of taxa relying on freshwater ecosystems and their connectivity extends well beyond fish to include birds, mammals, herptiles, invertebrates, and plants. For example, recent work on hemimetabolous (i.e., relying on both freshwater and terrestrial habitats) damselflies showed that habitat connectivity strongly influenced the proportion of colonized habitat patches (Streib et al. 2020).

In many ways, connectivity represents the template upon which freshwater species have evolved (e.g., Lytle and Poff 2004). As such, any alterations to flows and connectivity will have significant effects on freshwater species. In fact, the science on that matter is quite clear: fragmented freshwater systems have negative consequences for freshwater biodiversity (Gido et al. 2015; Dias et al. 2017; Brauer and Beheregaray 2020).

The impacts of fragmented longitudinal connectivity are well documented, particularly for fish and other strictly aquatic taxa. Barriers, both big and small, can affect the movement of aquatic species as they migrate upstream and downstream (Winemiller et al. 2016), but they also alter flows of water and organic matter that provide cues for seasonal movements, can flood upstream and alter downstream habitats (Ligon et al. 1995; Bunn and Arthington 2002; Birnie-Gauvin et al. 2017*b*), and prevent the exchange of individuals and genetic information between populations (Raeymaekers et al. 2008; Wilkes et al. 2019). Even if fish or other animals overcome a barrier, they likely 1) expend high levels of energy, 2) must swim further to find suitable habitat, 3) spawn in unsuitable habitat (or not at all), likely resulting in low survival of the young, or 4) become injured or die. As such, fragmentation of longitudinal connectivity is about much more than passage of aquatic species and has been directly linked to the extinctions, and local extirpations, of species (e.g., see Table 1 in Birnie-Gauvin et al. (2019)). In contrast, dams do not appear to impact the movement of freshwater birds, as they can fly over them, nor do they seem to impact their survival. In fact, reservoirs may provide habitat for birds that would otherwise be seasonally dry. However, freshwater bird species are still declining, so barrier impacts may still be negative in the long term via impacts on water quality or prey items, for example (McAllister et al. 2001). Dams and their reservoirs have been shown to fragment populations of terrestrial and semi-aquatic vertebrates (e.g., platypus in Australia (Mijangos et al. 2022) and terrestrial vertebrates in the Amazon (Benchimol and Peres 2015)).

Lateral connectivity is important for flows to floodplain wetlands and the habitats that they provide for freshwater and aquatic species. Floodplains are biologically diverse, with large populations of waterbirds, invertebrates, and fish. However, altered flow regimes caused by dams or other barriers can disconnect floodplains and seriously decrease species biodiversity and abundance (Boulton and Lloyd 1991; Halse et al. 1998; Kingsford 2000; Gergel et al. 2002; Opperman et al. 2009). When wetlands receive water via lateral flow, they also receive energy, matter, and organisms, setting in motion a cycle that shapes the entire ecosystem (Kingsford and Porter 1999; Jenkins and Boulton 2003), but dams alter this cycle. For example, reduced flooding in the Chowilla floodplain (lower Murray River basin, Australia) has resulted in a decreased abundance of invertebrates, which will likely result in the decline of native fish and waterbird species that rely on invertebrates to survive (Kingsford 2000). Dams and other forms of river management in that system divert almost 10,000,000 ML(megaliters) every year, causing flows to the Chowilla floodplain to be about half what they used to be (Maheshwari et al. 1995).

Vertical connectivity links the river channel to the hyporheic zone and plays a crucial function for sustaining baseflows as long as the water table remains above the stream bed (Delleur 1999). However, given the inherent complexity of groundwater aquifers and our inability to directly observe them, the underlying importance of groundwater–surface water connectivity for supporting freshwater biodiversity is commonly overlooked or misunderstood. The hyporheic zone itself provides habitat for a range of microbes and invertebrates, sometimes several kilometers away from the channel, which contribute to secondary production among other functions (Stanford and Ward 1988; Marmonier et al. 1992; Boulton 2007). Regional groundwater aquifers within a basin sustain the groundwater levels of near-stream alluvial aquifers that are essential for groundwater dependent ecosystems, including riparian and wetland habitats. Humans have reduced both lateral and vertical connectivity by altering patterns of water flow via water abstraction (particularly of groundwater) and dam building (Hancock 2002) and through land-use change (Gibert et al. 2009; Moldovan et al. 2012). This includes changes in the hydrologic cycle such as those caused by increased levels of impervious surfaces (Mojarrad et al. 2019) or reduced flows due to afforestation (Hughes et al. 2020) and sedimentation of waterways, which causes infilling and blockage of the hyporheic zone (Shrivastava et al. 2020). Although the effects of vertical fragmentation on higher trophic species are not well documented, they do exist, as exemplified by the reduced survival of salmonid eggs with reduced hyporheic flow (e.g., Bowerman et al. 2014).

The temporal dimension of connectivity is critical for the viability of many freshwater species. Freshwater processes are often driven by seasonal changes in flow and the frequency of flooding. Hermoso et al. (2012) highlighted the importance of considering temporal connectivity for freshwater fish, waterbirds, and turtles by demonstrating that integrating water residency time (i.e., an estimate of the time during which connections between aquatic habitats were available for them to access refugia) into prioritization processes (in addition to the usual spatial connectivity) increased water residency time by 40% in priority areas. In essence, the consideration of temporal connectivity helped to identify the periods with the longest spatial connections, and thereby maximize the role of freshwater as a refuge during dry periods. Furthermore, freshwater biota often have seasonal reproductive cycles. Interrupting these cycles has a dramatic impact on successful spawning and recruitment processes, which are temporal events.

Flows of sediment and other organic matter are also part of the natural flow regime and critical in shaping the physical template for fluvial ecosystems and associated aquatic habitats (Harvey 1991; Constantine et al. 2014). This affects, for example, the shape of riverbeds and spawning habitat for fish and other species. Sediment capture by upstream dams and other infrastructure can cause a cascade of impacts on fluvio-geomorphological dynamics and processes far downstream and reduce sediment delivery for floodplains and deltas alike, ultimately impacting coastal morphology and ecosystems and leading to increased rates of delta subsidence and coastal erosion (Vörösmarty et al. 2003; Petts and Gurnell 2005; Schmitt et al. 2017).

While many rivers and their floodplains around the world have been fragmented, there are still many large and small rivers that maintain high levels of connectivity. The connectivity of these systems is critical to remaining refuges for freshwater biodiversity (e.g., the Amazon and its tributaries, the Irrawaddy and Salween Rivers). Maintaining and restoring freshwater connectivity is one of the six actions required to bend the curve for freshwater biodiversity identified by Tickner et al. (2020). The main aim of the manuscript is to present a set of measures to protect and restore connectivity (Fig. 1) and to illustrate their potential for addressing connectivity issues by providing case studies that highlight successful implementation. A secondary aim is to provide a comprehensive overview of each of the measures, including a review of the current state of understanding of the effectiveness of the measure and areas for further research. The measures were selected using the collective knowledge of the assembled authors, and each expert conducted a review of scientific and grey literature for their respective measure and area of expertise. The sequence of presentation of the measures is in line with the mitigation hierarchy—i.e., first line actions should be focused on avoiding loss of connectivity (i.e., planning siting of infrastructure in locations with no or minimal impacts; putting in place protection mechanisms that safeguard connectivity of river corridors), where that is not possible, action can be taken to minimize or mitigate impacts (i.e., design of dams and other water-related infrastructure and operating dams in line with environmental flows), and finally where damage has already occurred, actions can be taken to restore the system (i.e., dam or other water-related infrastructure removal) (Arlidge et al. 2018; Gann et al. 2019). We also indicate both the step(s) of the mitigation hierarchy with which each measure is associated and the dimension(s) of river connectivity that the measure has the potential to protect or restore (Table 1).

Measures to maintain and restore river connectivity

Strategic planning for energy, water resources, and biodiversity

Dams, and particularly dams with hydropower, have been a primary driver of the fragmentation of large rivers worldwide, resulting in a loss of connectivity. The expansion of hydropower into undammed river basins is a leading current cause for the loss of free-flowing rivers and a threat of future conversion (Winemiller et al. 2016; Thieme et al. 2021). Multi-purpose dams and irrigation dams are also prevalent in basins around the world, with anticipated continued additions as climate change and aging infrastructure decrease available water storage (Baumgartner et al. 2021; McCartney et al. 2022). In their report for the World Bank, Ledec and Quintero (2003) argue that, in terms of environmental and social impacts, project location is the single most important decision about a proposed dam—and this is particularly true for connectivity impacts.

Regulatory and planning processes often require environmental assessments of dams that entail quantifying potential negative impacts, evaluating tradeoffs, and informing decisions about a proposed dam. However, in practice, environmental review tends to focus on single projects and is often applied after major decisions, such as those about project size and location, have been made. Because review often happens after major investments have already occurred and political momentum has been generated, the process rarely results in the rejection of a proposed project (Sadler et al. 2000). Thus, as commonly applied around the world, environmental review generally has little or no influence on project siting. Similarly, the current Hydropower Sustainability Standard (Hydropower Sustainability Secretariat 2021), developed through a process led by the International Hydropower Association, is generally focused, and applied, at the level of single projects and often after decisions about location have already been made.

Due to the limitations of project-level assessment for influencing the location of proposed projects, various organizations and researchers have recommended system-scale approaches to dam planning, such as Strategic Environmental Assessment (Sadler et al. 2000), needs and options assessments (World Commission on Dams 2000), and other basin-scale assessments and planning processes that integrate both conservation planning and infrastructure planning (Mekong River Commission 2016; Opperman et al. 2017*a*; Twardek et al. 2022). These approaches are intended to assess multiple different options for siting dams, quantify their performance across a range of social, economic, and environmental metrics, and, if possible, identify options that perform well across multiple objectives.

The range of options can be greatly expanded—and thus the potential for identifying options that perform well across multiple objectives can be increased—if the scale of planning extends beyond siting to include other alternative options for meeting resource needs. In the case of hydropower systems, this means expanding from hydropower planning to energy

Fig. 1. Illustration of measures that can support maintaining and restoring river connectivity.

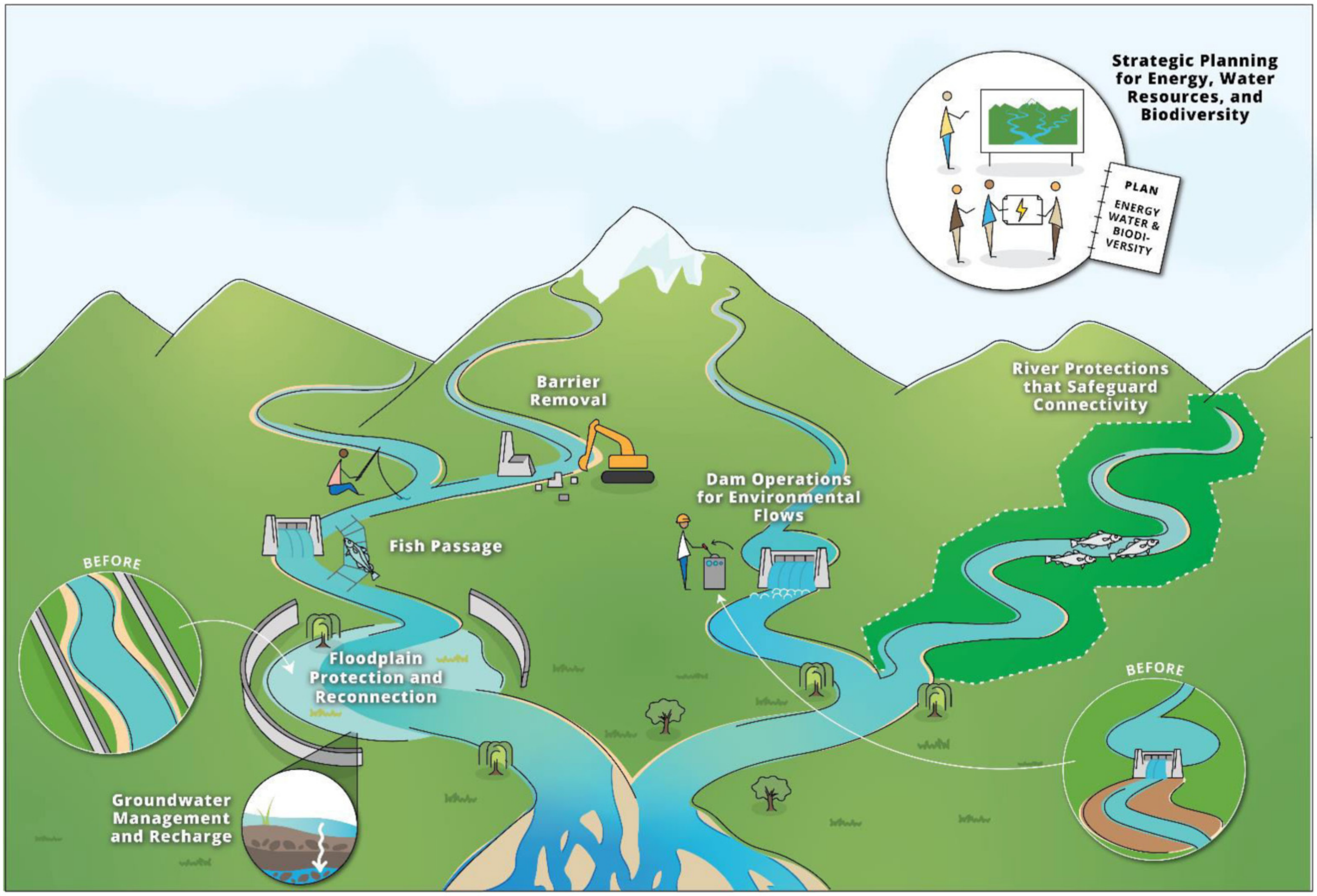


Table 1. River connectivity measures and their associated step(s) in the mitigation hierarchy and the dimension(s) of river connectivity that is potentially affected by the measure.

Measure	Mitigation hierarchy step	Dimension(s) of river connectivity potentially affected
Strategic planning for energy, water resources, and biodiversity	Avoid	Longitudinal, lateral, temporal, vertical
River protections that safeguard connectivity	Avoid	Longitudinal, lateral, temporal, vertical
Barrier design and fish passage	Minimize	Longitudinal
Dam operations for environmental flows	Minimize	Longitudinal, lateral, temporal, vertical
Barrier removal	Restore	Longitudinal, lateral, temporal, vertical
Floodplain protection and reconnection	Restore, Avoid	Lateral, vertical
Groundwater management/recharge	Restore, Avoid	Vertical

system planning (Opperman et al. 2023). For example, energy master plans or integrated resource plans (IRPs; see case study below) provide a framework to compare pathways for meeting projected energy demands, encompassing different generation technologies, storage options, transmission, and demand-side management, including energy efficiency and dynamic demand management. Within these frameworks, hydropower technologies can be compared against other technologies for meeting needs for generation and storage, allowing a broader range of options to be compared in terms of environmental and social impacts as well as grid performance and cost. Similarly, for the objective of water storage, achieving balanced outcomes across objectives, including maintaining free-flowing rivers, will be more likely if planning is expanded beyond that for storage dams to also include natural storage options, such as managed aquifer recharge (Yu et al. 2021).

Research has demonstrated that energy system planning can identify grid expansion pathways that are low-carbon, cost-competitive, and that minimize negative impacts on rivers. For example, Shirley and Kammen (2015) found that decentralized generation technologies (along with more realistic forecasts of future demand) could obviate the need for major new hydropower dams in Sarawak that would have displaced indigenous people. Opperman et al. (2023) demonstrated that Chile could meet energy demands without damming free-flowing rivers and that Uganda could meet future demand without additional hydropower projects—in both cases, at an essentially equivalent cost to options that involved greater expansion of hydropower. In essence, well-designed energy plans at the system-scale can be an effective measure for planning needed energy in ways that keep rivers free-flowing or well-connected.

Case study and IRP process in Zambia

Zambia's current electricity grid relies primarily on hydropower, which provides 80% of generation from 2.4 GW of installed hydropower capacity (Energy Regulation Board 2021), with much of that developed on the Zambezi River and its largest tributary, the Kafue River. Demand for electricity is rising rapidly, between 150 and 200 MW per year, due to economic growth and the need to dramatically expand access to electricity from the current electrification rate of 25%. Consequently, the government has proposed developing an additional 6,000 MW of hydropower capacity. However, climate variability and drought have already begun to impact current hydropower production, leading to energy shortages. To emphasize the criticality of energy security, on 6th January, 2023, the Kariba Dam, designed to provide the bulk of electricity consumed in both Zambia and Zimbabwe of 1080 and 1050 MW, respectively, hit a record low of 1.38% water level of usable water, according to the Zambezi River Authority. The Zambezi River Authority has been required to reduce generation activities (250 MW out of 1080 MW) until a further review of the substantive hydrological outlook at Kariba is undertaken. This is the lowest record low water level experienced since the 1995/96 period. These shortages have increased the urgency for developing new capacity as well as diversifying the energy mix.

As part of the government's plans to increase hydropower capacity, the 240 MW Ndevu Gorge Power Project was proposed for the Luangwa River, a tributary of the Zambezi and, at 1100 km, one of the longest remaining free-flowing rivers in southern Africa. The Luangwa serves as a key resource for 25 communities and flows through two iconic national parks that support abundant wildlife. Because the proposed dam would have had major negative impacts on these resources, the communities and conservation organizations opposed the dam, and in 2019, the Zambian government canceled the pre-feasibility study and halted the project.

To guide the expansion of Zambia's power system, the Zambian Ministry of Energy initiated a process to develop an IRP for the power sector for the next 30 years. The IRP process is focused on developing a long-term strategy to meet Zambia's projected energy demands in a sustainable, reliable, and affordable manner, including diversification of the Zambian energy mix to include other generation technologies such as solar and wind and storage, including pumped hydropower storage. The inclusion of a broader range of generation and storage options will make it more likely that Zambia can provide low-cost and low-carbon power for its people and economy while minimizing additional damming of free-flowing rivers. The IRP is also incorporating climate change scenarios into its system-scale planning approaches to support robust decision-making about energy options.

River protections that safeguard connectivity

A measure that has effectively safeguarded river connectivity in certain parts of the world is the designation of rivers as protected or conserved. There are a range of designation types that have protected rivers against fragmentation. In many countries, IUCN category I or II protections, like national parks, often prohibit the building of infrastructure for commercial purposes and/or that would significantly degrade natural ecosystems. In some countries, river-specific designations have also been created that explicitly prohibit the building of dams and other infrastructure that would degrade the free-flowing nature of the river. A newly emerging type of designation provides "rights for rivers", legally granting rivers the right to be recognized as living entities with inalienable rights.

National-level programs that have been enacted into law to specifically keep rivers free-flowing are relatively rare around the globe. The earliest example comes from the United States, where the US *National Wild and Scenic Rivers Act* of *1968* enabled the designation of free-flowing rivers with outstanding natural resource values as Wild and Scenic Rivers (U.S. Congress 1968). As of 2019, over 21,565 km of 226 rivers in 41 states and the Commonwealth of Puerto Rico were designated, representing less than one-half of one percent of the nation's rivers (NWSR 2019). Once designated, the free-flowing condition and essential characteristics of a river that existed at the time of designation are to be preserved and, if possible, enhanced. Between the 1970s and 2010s, several European nations put in place legislation that protects rivers from hydropower or other infrastructure development. These include the protection of the remaining major free-flowing rivers in Sweden, the designation of protected rivers in Finland under the Rapids Protection Act, the creation of a Natural River Reserves system in Spain, and a protection plan for watercourses across Norway (Schäfer 2019). Sub-national and national laws aimed at the designation of individual river protections have also occurred. For example, a state law in Minas Gerais protects the Cipó, São Francisco, Pandeiros e Peruaçu, Jequitinhonha, and Grande Rivers in Brazil; a 1976 national law protecting the Soča River and tributaries in Slovenia (then part of the former Yugoslavia) has prevented hydropower development; the Sarapiquí River in Costa Rica was protected from hydropower development and further mining concessions for at least 25 years under a national law in 2022; and the Bhagirathi River in India is protected by the 1986 Environmental Protection Act (Perry et al. 2021; RAFA 2022).

Rivers have been legally granted rights of personhood in several countries around the world. Although the motivation for these rights is often due to water quality degradation, maintaining river connectivity may also be defensible under the designated rights. Examples of legal designation of river rights come from New Zealand (Whanganui), Ecuador (Vilcabamba River), India (Yamuna and Ganges), and Colombia (Atrato River) (Perry et al. 2021).

In addition to river-specific protections, allocations of environmental flows or water reserves, if effectively implemented, can prevent the building of dams and other infrastructure that fragments rivers. For example, the environmental water reserve for the San Pedro Mezquital (decreed in 2014) has been part of efforts to prevent the Las Cruces hydropower dam from being built. Part of the argument used to prevent the dam has included that the dam would affect flows designated in the Environmental Water Reserve. In particular, the flows required to reach the mangroves downstream in the Marismas Nacionales Ramsar site as well as those required for social resources related to Indigenous People's rights (Salinas-Rodríguez et al. 2021).

However, designation of a river as a protected or conserved area does not guarantee that the river or river stretch will remain protected from development in perpetuity. An early example comes from Yosemite National Park in the US, where the Hetch Hetchy Dam was built within the national park boundaries in 1913 to supply water to San Francisco. Evidence that this is not an isolated incident comes from Thieme et al. (2020), who documented a total of 342 dams that had been built within protected areas around the world after their establishment. Nevertheless, river protection designations that explicitly safeguard river connectivity remain an important, and increasingly implemented, measure to ensure the health of rivers and keep them connected and free-flowing.

Case study: Vjosa National Park: steps toward protecting a free-flowing stronghold in Europe

The Albanian government has recently taken several important steps towards ensuring the long-term protection of the free-flowing nature of the Vjosa River. The Vjosa, one of the longest remaining free-flowing rivers in Europe, still flows 270 km nearly unimpeded from its source in the Pindus mountains in Greece to the Adriatic Sea in Albania. It is considered an extremely rare reference site for medium-sized rivers in Europe as its hydrological dynamics, including sediment flows and floodplain characteristics, remain in a near-natural condition. The gravel-bed river supports a uniquely intact river-dependent fauna typical of highly dynamic large rivers. These types of rivers have lost a large proportion of their former distribution in Europe. Several fish species native to the Vjosa depend on river connectivity for short- and long-distance migrations to complete their life cycles, including the endangered European eel (*Anguilla anguilla*). The river hosts 37 fish species, at least 267 distinct taxa of aquatic invertebrates, and hundreds of aquatic plants (Meulenbroek et al. 2021). The river has long been threatened by the development of hydropower dams along its course, but the Albanian government has recently canceled the Kalivaç and Pocem dams that were to be built on the mainstem of the river after intense pressure from civil society groups and local people. In June 2022, the Ministry of Tourism and Environment of Albania and the company, Patagonia, signed an agreement to work together to upgrade the protection level of the Vjosa River Basin and its free-flowing tributaries to an IUCN Category II Level National Park (Patagonia 2022). The intention is that the river system itself is protected, along its entire course within Albania.

Barrier design and fish passage

While the "effectiveness" of individual fish passages has been highly variable (Bunt et al. 2012; Noonan et al. 2012; Hershey 2021), biologically informed design of instream structures to account for the needs of migratory or otherwise mobile species has been shown to be able to reduce their impact on this aspect of river connectivity (Larinier et al. 2002; Williams et al. 2012). As far as practicable, all new structures should be designed in a way to eliminate or minimize their impact on migratory species. Particularly in the case of small structures (e.g., culverts), good design can effectively eliminate any barrier effect (Behlke et al. 1991). For larger structures (e.g., dams), where elimination of impacts is rarely a realistic option, the impacts on migratory species can be mitigated through, for example, the integration of fishways (Bunt et al. 2012) or, at facilities with turbines or other intakes, the use of structures or technologies that reduce entrainment and related mortality (Algera et al. 2020). In the case of existing barriers, efforts can be made to modify their design to reduce their impacts on freshwater biodiversity through removal (see barrier removal section), replacement with fish "friendlier" designs, or remediation. There are also instances where barriers are intentionally created to fragment systems and impede the migration of invasive species (McLaughlin et al. 2013). So-called "selective fragmentation" (Rahel and McLaughlin 2018) appears to be increasing in popularity and is a good reminder that there may be specific instances where maintaining or restoring full ecological connectivity may do more harm than good. Fortunately, there are a growing number of examples where facilities have been designed that can pass desirable species while blocking undesirable species (Kerr et al. 2021).

There is increasing evidence to show that small structures (e.g., culverts, fords, and low-head weirs) can have a disproportionate impact on river connectivity (Januchowski-Hartley et al. 2013; Evans et al. 2015). However, in many cases, careful design of these structures can render them almost invisible to aquatic organisms and provide for continuity of geomorphic processes. A good example is the "stream simulation" approach to culvert design (Cenderelli et al. 2011). Culverts have replaced bridges as the stream crossing of choice, particularly for smaller waterways, largely due to their lower cost and ease of installation (Frankiewicz et al. 2021). However, traditional hydraulic design approaches often constrict the channel cross-sectional area through the culvert, resulting in elevated water velocities that fish are unable to swim through and causing erosion at the culvert outlet, creating drops that can be unsurpassable to fish. The stream simulation approach to culvert design rethinks crossing design to account for both hydraulic conveyance requirements and the needs for aquatic organism passage and maintenance of hydro-geomorphic processes.

For both small and large structures, constructed passage devices can be installed at the time of construction, or retrospectively, to help mitigate or remediate their impacts and enable the safe upstream and/or downstream movement of animals and sediments (just downstream). Historically, this has focused on facilities designed to enable the upstream movement of fish past dams, and are most often referred to as "fishways" (Birnie-Gauvin et al. 2019). However, more recently, attention has increased on providing solutions to improve upstream passage efficiency at smaller structures, such as culverts and weirs (e.g., David et al. 2014; Goodrich et al. 2018; Leng et al. 2019; Magaju et al. 2021), and structures designed to facilitate downstream passage of sediments (and animals).

Fishways come in many forms (see Clay 1995), with highly engineered structures made of reinforced concrete among the most common. Each type has various benefits and limitations. For example, pool and weir-style designs require jumping ability (e.g., salmonids (Collins et al. 1962)) and, thus, are poor choices for benthic species. Denil fishway and vertical slot fishway designs have shown promise for passing more diverse fish communities, including some smaller bodied, weaker swimmers (e.g., Bunt et al. 2012). In some types of fishways, animals are trapped and then hoisted or transported by land, boat, or elevator past the barrier (e.g., Oldani and Baigún 2002; Pompeu and Martinez 2007). Over the last few decades, more nature-like fishways have been designed with the intention of better emulating a stream or river. The challenge with such designs is that a large footprint is needed to maintain low gradients, and this may not always be available, particularly at large dams or pre-existing dams. Small nature-like passages for very small dams (e.g., <1 m head) can be constructed by volunteers using hand tools and have proven effective for restoring connectivity for small-bodied fishes (Steffensen et al. 2013). However, larger facilities are more common, with one of the largest being at the Itaipu Dam in Brazil (Makrakis et al. 2011). In the latter example, some fish became residents in the passage structure, with only two species using it for complete passage, emphasizing the need to understand the ecological requirements and migratory behavior of fish when designing and assessing facilities.

To be successful, passage facilities must first attract aquatic species to the device, and then the species must be able to fully pass through it (Bunt et al. 2012). Competing flows and complex channels can confuse fish, which are often attracted to flows (rheotactic), particularly during migration, making it challenging to direct fish moving upstream towards the passage entrance. Through adaptive management, it has, however, been possible to optimize attraction flows for a given species or assemblage (e.g., Bett et al. 2022). Assuming a fish finds the entrance to the fishway, they must be able to pass it. Fish body size, morphology, condition, motivation, and more influence whether a fish will be successful in passing a given fishway (Castro-Santos et al. 2009; Bunt et al. 2012; Hershey 2021). So—even if a fish can ascend a fishway but is unable to locate it—it will fail. And similarly, if a fish finds the fishway entrance but is unable to ascend—it will fail.

A range of low-cost solutions for improving passage at small instream structures have also emerged in recent years (Frankiewicz et al. 2021). A key focus has been baffle design (e.g., weir baffles, offset baffles) to facilitate the upstream movement of fish through culverts. High water velocities within the culvert barrel can exceed the swimming capabilities of fish, preventing them from passing upstream. The installation of baffles can reduce bulk velocities and create low-velocity boundary layers and resting zones that enable fish to successfully move upstream. Efforts have also been made to design fish ramps to overcome drops at culvert outlets (or low-head weirs). These include rock-ramp (e.g., Muraoka et al. 2017) and artificial baffled ramp designs (e.g., Baker 2014) and have recently extended to exploring the relative passage performance of native versus exotic species to design selective passages that intentionally exclude exotic species (e.g., Franklin et al. 2021).

Enhancing the upstream movement of organisms has received the most attention in fish passage research and practice (Silva et al. 2018), but developing solutions to restore downstream passage is a priority and is receiving increasing attention (Lennox et al. 2019).

When fish "go with the flow" downstream, that often means entrainment in turbine or flood pump intakes (Boys et al. 2021). Fish "friendlier" turbine and pump designs can reduce fish mortality and improve downstream connectivity (Buysse et al. 2014; Watson et al. 2022). Similarly, operational changes can reduce entrainment and increase passage success (Baker et al. 2020). Alternatively, bypass facilities have been built to collect and direct fish to safe paths, and the use of various behavioral guidance methods (e.g., louvers and flashing lights) has proven somewhat effective for guiding some fish toward safe areas. For example, Scruton et al. (2003) report on the use of a louver system at a bypass to successfully guide most Atlantic salmon smolts to safe passage. However, it is clear that behavioral guidance that exploits sensory physiology mechanisms requires a nuanced understanding of a given species and contextual information about a site, meaning its effectiveness can be highly variable (Elmer et al. 2021). Sediment bypass tunnels have been constructed to enable the downstream movement of sediment (Boes et al. 2014; Kondolf et al. 2014) although they remain rare. Although conceptually it is possible to have a single structure that passes both sediment and fish downstream (Foldvik et al. 2022), to our knowledge, no such facilities have been tested.

Most fish passage structures are built and then never formally studied to determine their effectiveness (Katopodis and Williams 2012). Furthermore, where assessments are carried out, measures of "effectiveness" are highly variable (Bunt et al. 2012; Noonan et al. 2012; Hershey 2021). Many of the first fishways and those that have been most studied were purpose-built for salmonids, which are strong swimmers with good jumping abilities (Birnie-Gauvin et al. 2019). Not surprisingly, passage devices designed for salmonids have not performed well for other species (Mallen-Cooper and Brand 2007). As designs have diversified to meet the needs of different types of species in the last decade, there is growing evidence that fish passage is possible for non-salmonids (reviewed in Bunt et al. (2012)). There have also been several cases where small modifications in the design or operation of devices have greatly enhanced passage (e.g., Bunt 2001; Naughton et al. 2007). Engineers and biologists working collaboratively can enhance the likelihood of developing effective fish passage solutions (Williams et al. 2012). Fish passage can also have broader benefits to other taxa. For example, the installation of a fishway along an Australian River enabled recolonization by freshwater molluscs upstream given the role of fish as glochidial hosts (Benson et al. 2018). There are relatively few examples of purpose-built facilities for other taxa.

While fishways and other fish passage solutions have facilitated the passage of aquatic species and sediments in certain cases, their ability to fully mitigate the blockage of species and sediment passage comprehensively is limited. Entrainment or impingement of aquatic species can also result in direct losses, including mortality (e.g., turbine strikes (Algera et al. 2020)). Consequently, structure removal or replacement with fish "friendlier" designs remains a priority for restoring connectivity. Nonetheless, there continue to be efforts to improve the effectiveness of mitigation for infrastructure that limits connectivity or contributes to mortality through facility design. Increasingly, solutions are emerging that function with a diverse fish community (or broader assemblage of animals) in mind, and more effort is going into evaluating the success of remediation to support design and operational refinements (e.g., ensuring fishways are maintained and do not become clogged with debris), such that fishways and other solutions can play a role in mitigating some of the impacts of connectivity disruption.

Case study: fishways in the lower Mekong river in Laos

The Mekong River Basin is home to significant freshwater fisheries diversity (over 800 species), which is currently under threat from river infrastructure and hydropower projects (Ferguson et al. 2011). These are blocking important migration pathways for migratory fish. There have been significant efforts to improve riverine connectivity through the construction of fish passes (or fishways) (Baumgartner et al. 2019). Fish passage technologies to assist connectivity were initially piloted and co-designed with local communities (Baumgartner et al. 2012). Work focused initially on vertical slot fishways and expanded to submerged orifice and "cone" designs. The experimental proof of concept was first undertaken to establish that fish would use the technology, and a cone fishway was selected as the best candidate for a permanent installation (Baumgartner et al. 2012). The pilot stage was extremely successful. Over 100 species made use of the "cone" fishway, and fishers began reporting catches of species that had not been seen in over 20 years (Baumgartner et al. 2022).

Upon completion of the pilot stage, these structures are now being scaled into increasing numbers of dam and irrigation projects (Campbell and Barlow 2020). Over 30 structures have been put in place in the Lower Mekong Basin (Fig. 2). The first-ever fishway in Vietnam has just been completed. The case for implementing these measures more widely was based on two major elements. First, there was a need to develop the financial case. A decision support tool was developed to estimate, in economic terms, the return on investment and benefits to local communities from increased protein provided by an improved fishery (Cooper et al. 2019). Proponents could then quickly determine the relative viability of a project based on expected returns. Second, there was a need to understand the motivations and abilities of actors in the decision-making ecosystem to make the business case in a way that resonated and allowed for the inclusion of this new approach into development programs (Salter et al. 2020; Conallin et al. 2022*a*).

Sites where these interventions have been applied are experiencing significant increases in fish biodiversity and contributing to community cohesion. Importantly, many fishers are also reporting catching fish that have not been seen for many decades (Millar et al. 2019). Translating these early successes into region-scale donor investments is what is needed to truly bend the curve (Conallin et al. 2022*b*). Current initiatives are focused on building human and institutional capacity to ensure decisions regarding the implementation of fish-friendly solutions are "automatically" considered in future infrastructure development projects (Baumgartner et al. 2017). Importantly, this program succeeded owing to the inclusion of local communities in the design, the implementation of a robust monitoring program, the application of the principles of adaptive management to future designs, and the development of a comprehensive evidence base to support enhanced decision-making.

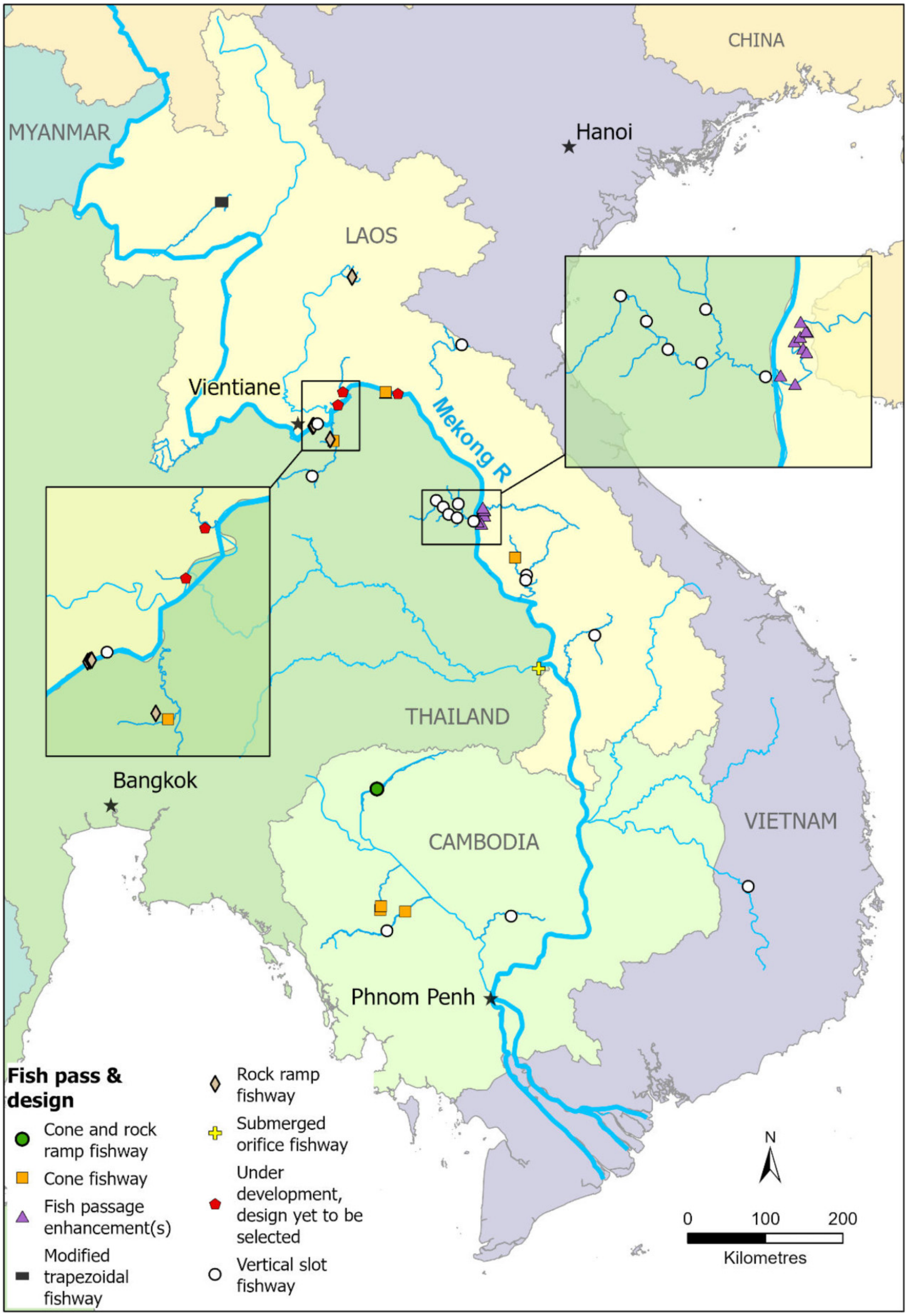
Dam operations for environmental flows

Environmental flows are defined as the hydrological regime required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on them (Acreman 2016). Environmental flows are often, although not exclusively, set within the context of the reoperation of existing infrastructure, such as dams and diversions. As such, they are an important mitigation measure to reduce the impacts of infrastructure systems on the natural flow regime and freshwater ecosystems. They can be a particularly useful mitigation measure for restoring lateral connectivity. Societal choice plays a significant role in setting the objectives for environmental flows. For example, changes in the flow regime can be set to meet cultural (e.g., flow needs for certain spiritual activities), recreational (e.g., river rafting or kayaking), or environmental (e.g., flood flows to cue spawning or to inundate floodplain nursery habitats) objectives. We refer the reader to Arthington et al. (in this special issue), who review a set of case studies where environmental flows have been successfully implemented and provide a summary of key enabling factors for implementation.

Barrier removal

Where barriers exist, their removal is the only solution that fully restores all aspects of connectivity (Bednarek 2001; Birnie-Gauvin et al. 2019). Removing barriers, specifically those that are unsafe, obsolete, financially unviable, or even those whose ecological impacts are too great to ignore, pro-

Fig. 2. Locations and types of fish passes planned and/or constructed in the Lower Mekong Basin.



vides an unprecedented opportunity to restore connectivity across its four dimensions. Removing barriers restores the natural flow regime (Poff et al. 1997; Bednarek 2001) and the habitat that a multitude of organisms depend on to feed, spawn, and seek refuge (Birnie-Gauvin et al. 2017*a*; Bubb et al. 2021). It restores substrate, macrophyte growth (Hill et al. 1993), the flow of sediments (Poff et al. 1997), and temperature regimes (Yeager 1994; Bednarek 2001). Importantly, barrier removal increases the abundance and (often) diversity of fish and invertebrate species (e.g., Hill et al. 1993;

Birnie-Gauvin et al. 2018; Ding et al. 2019; Bubb et al. 2021), as well as riparian vegetation (Brown et al. 2022). Moreover, it reconnects aquatic habitats and the passage of organisms within and between these habitats (Dynesius and Nilsson 1994; Weigel et al. 2013; Birnie-Gauvin et al. 2018; Kukuła and Bylak 2022). In essence, barrier removal means restoring a river to its natural state, so it is perhaps not surprising that the dam removal movement is growing (see, for example, Dam Removal Europe; www.damremoval.eu).

Of course, restoring connectivity through removal can also permit the movement of invasive species into a system or farther upstream within an already invaded system, creating challenges for managing fragmentation that maintains hydrological connectivity while blocking invasion from non-native species (Rahel 2013). Although barriers designed to deter aquatic invasive species have shown moderate success, most studies have been too short to detect adequate ecological impacts, highlighting the need for refining the design and operation of such barriers, particularly if they are to enable the passage of native fauna (Jones et al. 2021). For example, the eradication of non-native rainbow trout above a barrier has enabled native mountain galaxias to recolonize the area above the barrier, but not below, where rainbow trout were still present (Lintermans 2000). So, although barriers may prevent the movements of invasives, they may also affect those of native species, so careful consideration is required in these instances.

Barrier removal is a restoration measure that can have direct ecological, social, and economic benefits (Bednarek 2001; O'Connor et al. 2015; Bellmore et al. 2017; Schiermeier 2018; American Rivers 2019). In addition to the ecological ramifications of damming, the safety hazards of aging barriers and economic considerations are among the top reasons for removing barriers—that is, removal is typically less costly in the long term than the costs of maintaining a barrier (Pejchar and Warner 2001; Doyle et al. 2003; Silva et al. 2018). A return-on-investment analysis of barrier removal projects in the North American Great Lakes found that removing both dams and road culverts had the greatest potential to benefit fishes, and demonstrates the importance of both small and large removal projects (Fitzpatrick and Neeson 2018). Moreover, there now exist several systematic methods for prioritizing barrier removal, including cost–benefit analyses, spatial graphs for habitat suitability modeling and several other publicly available tools (Whitelaw and Macmullan 2002; Kemp and O'Hanley 2010; Branco et al. 2014; Hermoso et al. 2021; Garcia de Leaniz and O'Hanley 2022).

The removal of barriers as a policy priority has been limited. The EU policy (the EU Biodiversity Strategy for 2030 has a target that at least 25,000 km of rivers will be restored into free-flowing rivers by 2030) and the recently passed US infrastructure bill included US$2.3 billion for increasing hydropower capacity without adding new dams (through retrofits and powering non-powered dams) and for the removal of aging dams to restore rivers and improve public safety. In Southeast Asia and Oceania, there has also been a rise in barrier removal cases over the past two decades (Ding et al. 2019). In Australia, New South Wales implemented the "fish superhighways" project, which is the largest fish passage remediation program in Australia. Despite this movement, a recent review indicates that within the US, less than 10% of the 1200 dams removed have been scientifically evaluated. Thus, the need for long-term monitoring and robust study designs must be addressed to predict the impacts of removal and inform decision-making (Bellmore et al. 2017). Stakeholder involvement is crucial to successful removal projects and can even lead to restorative environmental justice in some cases. The Ottaway, Penobscot, and Elwha rivers are examples where native American tribes have played a key role in removals by bringing cultural, economic, and legal resources into the process.

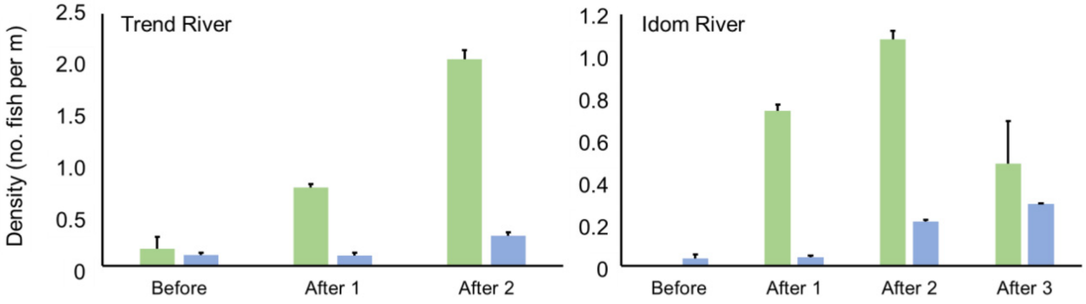
Barrier removal case studies: dam removal in Denmark and South Africa

Denmark is considered a leader in river restoration, with no new barriers built since 1973 and hundreds removed. Given its relatively flat landscape, most barriers in Denmark are small and yet have important repercussions on habitat availability (Birnie-Gauvin et al. 2017*a*) and fish populations (Birnie-Gauvin et al. 2017*a*). Removal of these barriers—primarily small hydropower dams and weirs used in the fish farming industry—has led to rapid and impressive benefits at both local and catchment scales, as well as across the lifecycle of salmonids (brown trout *Salmo trutta* and Atlantic salmon *Salmo salar* (Birnie-Gauvin et al. 2017*a*; Birnie-Gauvin et al. 2017*b*; Bubb et al. 2021). River Villestrup, where six weirs were removed, is a striking example where the trout smolt run went from 1600 to just under 20,000 and the spawning population from 350 to 3600 (Birnie-Gauvin et al. 2018). The Trend and Idom Rivers are just two of the many rivers where young-of-the-year trout were essentially absent but where their density exploded in the 1–2 years following removal (Fig. 3).

In some regions, particularly in developing countries in Africa and South America, dam removal has gained little momentum, if any. In Africa, the only known barrier removals are in the Kruger National Park (KNP), a biodiversity hotspot in South Africa, where conservation managers have removed 26 obsolete dams. These removals form part of the water management plan that allows for the removal redundant barriers with the aim of improving natural fish migration patterns and restoring natural aquatic ecosystem processes. The KNP is given the mandate to independently manage the region, which is a biodiversity hotspot in Southern Africa and an important tourist attraction for international travelers.

The Shingwedzi River in the KNP is a biodiversity hotspot with 27 fish species. However, in 1977, following the construction of the Kanniedood Dam, the natural fish migration patterns were restricted. A simple weir-pool fish pass was built on the dam but was largely (90%) inoperable (Olivier 2003; Heath et al. 2005). In 2012, part of the dam was damaged by a flood, and in 2017, with assistance from the South African National Defense Force, it was demolished. Following the removal of the dam, a significantly greater diversity of cyprinids and siluriform fishes has been observed, increasing the diversity of fish upstream of the barrier from <10 species

Fig. 3. Density (number of fish per m^2) of young-of-the-year (green) and older (blue) brown trout (*Salmo trutta*) in river Trend (left) and Atlantic salmon (*Salmo salar*) in river Idom both before and after removal.



between 1978 and 2018 to >25 species within three seasons after the removal, and this diversity has been maintained into 2019 and is expected to increase. The important increase in diversity of fish in the Shingwedzi has made a considerable contribution to the conservation efforts of South African National Parks and demonstrated the value of connectivity management in the region.

Floodplain protection and reconnection

Floodplains are among the most productive and diverse ecosystems on Earth, with productivity and diversity both strongly influenced by hydrological connectivity between floodplains and river channels (Opperman et al. 2017*b*). Floodplains, defined as landscape features that are periodically inundated by water from adjacent rivers (Opperman et al. 2010), also have a variety of characteristics that have long drawn people to live and work on them, including flat topography, fertile soils, and proximity to rivers. Due to intensive settlement and the development of floodplains, river floods have become one of the costliest forms of natural disaster in recent years, with $82 billion in damages in 2019 (Aon 2019). A common response to managing flood risk has been the construction of infrastructure intended to avoid inundation by hydrologically disconnecting floodplains from rivers through physical barriers (levees or tide gates) or by lowering discharge to reduce flood peaks (dams with reservoirs managed to regulate floods). Due to the widespread construction of dams and levees, floodplains have become disconnected from their rivers across much of the world, particularly in temperate regions. Due to this widespread hydrological disconnection—and subsequent conversion to agricultural or urban land uses—Tockner and Stanford (2002) have described floodplains as among the most converted and threatened ecosystem types on the planet.

Although dams and levees are crucial infrastructure for public safety in many places, flood managers are increasingly acknowledging that a narrow reliance on grey infrastructure can create problems. For example, infrastructure can give people the impression that flood risk has been eliminated, not just reduced, leading to dramatic increases in population within areas affected by levees, and therefore greatly increasing the people and property at risk should a levee fail or be overtopped (the "levee effect"; Tobin 1995). Further, in many countries, including the US, budgets have failed to keep pace with the maintenance needs of aging infrastructure, and, as a result, there is a considerable backlog of maintenance needed to ensure that dams and levees are safe and effective. For example, the American Society of Civil Engineers gives both dams and levees in the US a letter grade of "D", with dams requiring approximately 100 billion USD in rehabilitation costs and federally managed levees needing 21 billion USD in rehabilitation costs (the cost for non-federal levees is unknown but likely far more) (American Society of Civil Engineers 2021).

Due to the limitations of strict reliance on grey infrastructure, flood managers now promote a "diverse portfolio" of flood-management approaches, including Nature-based Solutions (NbS) that involve strategic reconnection of floodplains—or maintaining existing connectivity. By strategically allowing floodplains to flood, they can provide conveyance or storage of floodwater to reduce flood risk for other locations, such as cities or valuable farmland. Maintenance of existing connected floodplains can be achieved through zoning or acquisition, including easements, of floodplain areas to keep them in land uses compatible with flooding. For example, protection of the 10,000-acre Otter Creek Swamp Complex along Otter Creek (Vermont) has proved to be successful at reducing flood risk for downstream communities. During Hurricane Irene, which produced record-breaking flood levels and damage across Vermont in 2011, the flood peak in the town of Middlebury was cut in half and delayed by a week because floodwaters spread out across the Otter Creek Swamp Complex. Researchers estimated this saved millions of dollars in damages (Watson et al. 2016).

Reconnection of floodplains can occur through setting levees back from the river, increasing the area of floodplain available for conveyance, or through features such as flood bypasses or floodways. Levee setbacks have proven to reduce flood risks through various applications in the United States and Europe and can have added benefits for biodiversity. Serra-Llobet et al. (2022) describe case studies from Germany and California. Flood bypasses are crucial components of flood-management systems for the Lede and Sacramento rivers (Sommer et al. 2001; Opperman et al. 2017*b*).

NbS are intended to provide multiple values beyond their primary objective. For example, in addition to reducing flood risk, NbS projects involving floodplain reconnection or protection can provide diverse benefits, including groundwater recharge, water quality improvements, and the provision of a range of resources for people (fish, wildlife, and materials), as illustrated in the case study below.

Case study: protecting floodplains along the Ing river in Thailand for community benefits

In 2015, the federal government of Thailand proposed developing a Special Economic Zone (SEZ) that would have resulted in the conversion of 500 hectares of floodplain forest, and the filling of wetlands along the lower Ing River, a tributary of the Mekong River. In response, the Boon Rueang Wetland Forest Conservation Group (BRWFCG) pushed for protection of the seasonally flooded forest. The villagers and BRWFCG demonstrated that this forest is essential for their livelihoods, contributes to the local economy, and provides diverse social, cultural, and ecosystem services, including flood-risk reduction. The Regional Community Forestry Training Center for Asia and the Pacific (RECOFTC), an international organization focused on community management of forests (United Nations Development Programme (UNDP) 2021), calculated the ecosystem services of the floodplain forest would cost $4 million annually to replace, considering both substitute services and the loss of livelihood and revenue. The floodplain provides habitat for native wildlife and fish (Living River Association 2015, 2017) and sequesters carbon (Living River Association 2021). Further, the floodplain stores and conveys floodwaters and was credited with sparing the village from inundation during a major flood in 2010. By documenting the multiple benefits provided by a floodplain, including flood-risk reduction, the village and BRWFCG were successful in convincing the government to withdraw the SEZ proposal in 2018. In 2020, BRWFCG received the United Nation's Equator Prize for "outstanding community efforts to reduce poverty through the conservation and sustainable use of biodiversity". The villagers and BRWFCG are currently working to protect other floodplain forests along the Ing River into a riverine wetland recognized under the Ramsar Convention.

Groundwater management/recharge

Hyporheic zones include the streambeds, banks, and floodplains where the mixing of water that is episodically (naturally) recharged from flood flows, mixes with the more constant inflows of groundwater from surrounding aquifers. Hyporheic exchange flows can be hotspots for biogeochemical processing (Boano et al. 2014), sustaining unique fauna (Boulton 2007), providing thermal refugia (Casas-Mulet et al. 2020), and contributing to the success of specific life cycle stages such as fish spawning (Malcolm et al. 2008). Streamflow depletion through direct exploitation of groundwater reduces inflows to surface waters and, in more extreme cases, drives surface flow intermittency (de Graaf et al. 2019). Channel modification (e.g., physical straightening or bed armoring) lessens vertical connectivity by shrinking and reducing the porosity of the hyporheic zone (Kondolf et al. 2006). Efforts to sustain and restore vertical and horizontal connectivity to support ecosystem health must, therefore, address both groundwater use and river geomorphology (Boulton 2007).

Changes in connectivity, can be controlled by conjunctive management of groundwater and surface waters within sustainable limits (Gleeson and Richter 2018; Zipper et al. 2022). Approaches to managing or protecting groundwater sources include the acquisition of land, water rights, conservation easements, or water transactions, including fallowing agreements, leases, or incentive payments used to restrict the magnitude, timing, or location of pumping. On-farm irrigation efficiency measures, crop switching, and municipal water conservation policies and programs may also be used to reduce groundwater withdrawals.

In addition, managed aquifer recharge projects can also be designed specifically to sustain freshwater systems using predictive hydrologic models to meet the specific water needs of aquatic, riparian, or wetland freshwater species or communities (Leake et al. 2008; Lacher et al. 2014; Saito et al. 2021). Possible sources of water for aquifer recharge include high-quality treated effluent and the capture of stormwater runoff from urbanized areas or watersheds in poor condition. This can improve water quality, reduce erosion and sedimentation, and enhance groundwater storage for natural systems in downstream locations.

Successful implementation of these strategies relies on effective groundwater governance (FAO et al. 2016). Key characteristics of successful governance include effective institutions that integrate co-management with stakeholders; policies and resourcing that support local, regional, and global management goals; legal systems with the capacity to create and, importantly, implement and enforce laws effectively; and local knowledge and scientific understanding of groundwater systems (FAO et al. 2016; Closas and Villholth 2020; Gleeson et al. 2020; Molle and Closas 2020*a*, 2020*b*). Mechanisms include comprehensive plans, municipal zoning, the transfer of development rights, government requirements for regional groundwater sustainability, and reserved water rights that pertain to groundwater.

Alongside managing the effects of depletion, restoring geomorphological controls on vertical connectivity has received increasing attention. Flushing of fine sediments from interstitial spaces to mitigate colmation and restore natural vertical connectivity can be achieved using flushing flows (e.g., Mathers et al. 2021) or by direct removal (e.g., Ward et al. 2018). Increasingly, efforts are being made to create "engineered hyporheic zones" (sensu Tewari et al. 2021) by modifying stream channels to induce hyporheic flows. This includes the creation of bedform structures like riffles and gravel bars, and instream geomorphic structures such as meanders, log jams, and cross vanes (Tewari et al. 2021). The addition of large trees generates vertical mixing between the stream channel and hyporheic zone (Krause et al. 2014) and has been shown to alter hyporheic meiofauna communities (Magliozzi et al. 2019*a*) and stream temperatures (Klaar et al. 2020). Similarly, the installation of cross-vanes (Daniluk et al. 2013) and beaver dam analogs (Wade et al. 2020) has been shown to increase vertical water fluxes and improve groundwater–surface water interactions, while hyporheic exchange flows were generated by constructed riffles in a lowland stream (Kasahara and Hill 2006). The effectiveness of these interventions can likely be improved through strategic spatial planning of restoration efforts by aligning interventions with natural areas of hyporheic exchange (Magliozzi et al. 2019*b*).

Case study: San Pedro Riparian National Conservation Area, Arizona, USA

A collaborative group of 21 local, state, and federal entities (uppersanpedropartnership.org) developed a regional hydrologic monitoring program (Gungle et al. 2016) and predictive models (Pool and Dickinson 2007; Leake et al. 2008) to evaluate a wide range of groundwater management alternatives to protect and enhance baseflows and shallow groundwater required for the San Pedro Riparian National Conservation Area (SPRNCA) in Arizona. Hydrologic monitoring data were used to calibrate modeling scenarios (Lacher et al. 2014) that estimated the impact and benefits to riparian ecosystem health from proposed water policies, land and water protection, and infrastructure projects.

Over 20 years, permanent protection of more than 6,000 acres of hydrologically sensitive areas was put in place along 25 miles of the SPRNCA, in addition to regional land use policies and ordinances, and federal, municipal, and agricultural water efficiency measures that reduced the annual groundwater deficit in the region from 10,700 acre feet to 3,600 acre feet per year, even with a more than 9.4% population growth rate during that same period (USGS 2022). As of 2022, three managed aquifer recharge projects were in operation, and two more were under design to help sustain the ecological values of the SPRNCA using high-quality treated effluent and stormwater runoff. Between 2015 and 2021, 31,000 acre-feet of groundwater was recharged or retired from pumping from strategic locations (https://ccrnsanpedro.org/about/cite). Lastly, an overarching adaptive management framework for regional groundwater management, which addresses future monitoring, modeling, and needs for additional projects or policies, was put in place by a Memorandum of Understanding between federal and local governments, and is available at https://uppersanpedropartnership.org/.

Overcoming implementation challenges

Actions to maintain and improve river connectivity should aim to avoid and minimize the creation of new barriers that fragment rivers (aside from specific instances when selective fragmentation is essential for invasive species control), while also addressing the significant legacy of existing structures that restrict the movements of aquatic organisms and disrupt hydro-geomorphic processes. Challenges to achieving these goals include a lack of understanding of the problem, weak policy directives, trade-offs with apparently conflicting objectives (e.g., increasing renewable energy associated with achieving net zero targets), status quo bias in structure siting, design and operation, and inadequate resourcing.

As we look toward the future, we know that there will be increasing demand for new infrastructure, which will fragment freshwater environments if a business-as-usual approach continues. For example, projections show that an estimated $90 trillion is expected to be invested in new infrastructure globally by 2030 (Bhattacharya et al. 2015). This includes networks of new roads and associated culverts, levees, and dams for energy production and water storage (Alamgir et al. 2017; GWP and IWMI 2021; IEA 2021). Ensuring efficient use of resources—both energy and water—should be a front-line response of governments and utilities to, in the first instance, limit the rate of increase in demand and, thus, the number of new structures needed for energy production and water storage (IEA 2021). Integrated water storage, which takes advantage of both built and natural storage, will similarly be important for ensuring that natural functions and services are maintained in ways that serve societal and nature's needs (Dillon et al. 2022). Siting, structure design, and operation, where new infrastructure (culverts, levees, dams, and others) is deemed necessary, will be critically important for minimizing impacts.

Reconnection of freshwater systems that have already been fragmented can result in dramatic and quick improvements to the health and productivity of aquatic ecosystems (Tonra et al. 2015). Decision-makers, including public agencies and elected officials, are much more willing to solve the problems that they believe are actually "solvable" (as opposed to intractable), if only incrementally at first. However, the public, policymakers, and managers are often unaware that fragmentation is even a problem. Part of the reason for this is that there are no routinely used measures of connectivity in the state of environment monitoring and reporting in many parts of the world. There are also often limited, publicly accessible barrier databases and standardized methodologies to assess impacts. Putting these in place and sharing them with the public helps raise the profile of the issue of disconnectivity and helps understand the scale of the problem. Efforts to build better barrier inventories (e.g., Belletti et al. 2020; Franklin et al. 2022; USACE 2022) help, especially when they are accessible. Interactive tools like the AMBER barrier tracker app and the NZ Fish Passage Assessment Tool app are making it easy for people to assess and report structures as well. However, there has also been a history of mitigation (e.g., construction of fish passages), yet there has been no monitoring to determine if such devices are actually effective (Cooke and Hinch 2013). This has led to concerns about further investment in expensive fish passage facilities that may not work. There is a need to further build the evidence base to ensure that mitigation efforts achieve desired conservation gains (Silva et al. 2018).

The social context behind restoration and conservation should not be ignored. Communities and individuals can be catalysts for ensuring implementation, though this requires a change in the perception of what rivers can actually offer; rivers are not merely resources fulfilling human needs for drinking water but are home to a huge diversity of organisms (Birnie-Gauvin et al. 2023). Changing this perception is key to successfully engaging with society's diverse groups. Empowering communities with knowledge and understanding of the situation is fundamental to enabling them to act. For example, the Ndevu Gorge Dam was proposed on the Luangwa River in Zambia, which would have major impacts on the South Luangwa National Park, communities, and the tourism sector in the region. Local communities and chiefdoms were engaged in an educational campaign about the proposed dam; a model of the potential reservoir was created to demonstrate the extent of flooding; and leaders and citizens were mobilized to speak out about the dam. After months of engagement and outreach, the government ultimately canceled the dam and has continued its efforts to identify more sustainable options (WWF 2019). Monitoring programs and other community-based partnership efforts that directly engage community scientists, community leaders, and others can also build such a common understanding over time, especially when diverse perspectives and knowledge systems are engaged. Evidence suggests that increased intensity of local participation tends to generate policies with increased quality, and even when the outcomes are not "better", stakeholders learn and feel empowered (Kochskämper et al. 2016).

In the absence of awareness and understanding of the issue, as well as good data to characterize the size of the problem, there is often little incentive for strong policy. Strong policies backed by implementation make a difference. In some parts of the world, freshwater connectivity is beginning to be incorporated into policy. For example, New Zealand has established national environmental standards for the design of new structures (New Zealand Government 2020) and compulsory policy objectives to maintain or improve fish passage and develop fish passage action plans setting out actions to remediate existing structures (Ministry for the Environment 2020).

Even where strong policies exist, there will always be tradeoffs against other policy imperatives. In most cases, infrastructure projects are assessed and planned on a project-by-project basis without considering the context of the basin and the needs for movements of water, species, and organic matter across the landscape. Decisions that consider portfolios of projects and scenarios of impacts on the supply of ecosystem services, biodiversity, energy, water, and other variables will be most likely to be beneficial to society and nature over the long term. Examples of such planning processes are few and far between, but should be held up as examples of what is possible. For example, a hydropower relicensing process in the Penobscot Basin in Maine, USA, expanded beyond single dams to include the hydropower system in the lower basin. By seeking solutions at that expanded scale, the process resulted in the removal of two aging dams, fish passage improvements on two other dams, and equipment and operational changes at several other dams. These changes resulted in total electricity generation from the Penobscot Basin remaining equal (or slightly increasing) to the level prior to dam removal, but with dramatic increases in habitat available to migratory fish; numbers of river herring increased from 20,000 before dam removal to nearly 2 million in 2016 (Opperman et al. 2011). Science (including structured decision-making approaches; Dolson et al. 2021) can and should be used to directly support these processes. The use of predictive models and other related tools should not be restricted to only defining future problems but also exploring and identifying solution-based alternatives that benefit biodiversity/connectivity while also being socially and economically acceptable to local communities.

In certain instances, mindsets and thinking are resistant to change, creating a barrier for implementation (Jørgensen and Renöfält 2012). For example, dam removal on the Selune River in France was protested due to fear of what would happen after the removal (Birnie-Gauvin (personal communication)). Human nature often tends to bias keeping of the status quo and reverting to known approaches or designs. A visual rendering of what the site will look like can help alleviate some of the public's concerns. Sharing stories of the "early adopters" who have successfully implemented required changes and their lessons learned can also go a long way toward building the confidence of other communities and decision makers to try innovative approaches. To create a large-scale shift in perspectives among technical experts, educational programs and training for engineers and planners regarding the planning, siting, and design of both grey and natural infrastructure are needed. Several examples of these types of programs already exist, such as the US Army Corps of Engineers' engineering with Nature program, Northwestern University's Center for Engineering Sustainability and Resilience, and University of Georgia's Institute for Resilient Infrastructure Systems. In New Zealand, the establishment of a multi stakeholder, cross-sectoral fish passage advisory group that undertook codesign of guidance and tools on how to mitigate impacts through structure design and operation has proven successful in allowing greater uptake of new approaches. Wider dissemination and uptake of new approaches to planning, siting, design, and operation across a broader section of experts, educational stages, geographies, and governmental and private entities will be necessary for whole-scale adoption.

Where policies exist and decision-makers have been convinced either to maintain or reconnect freshwater systems, a lack of resources is inevitably a barrier. Hence, there is a need for prioritizing either the barriers that will be removed or the freshwater systems that should remain connected. Numerous tools and approaches have been developed that can support decision-makers in prioritizing efforts (e.g., O'Hanley and Tomberlin 2005; Kemp and O'Hanley 2010; King et al. 2017; Garcia de Leaniz and O'Hanley 2022). For example, analyses can be undertaken that prioritize certain rivers or river stretches to keep connected for a number of the services that they provide (e.g., swimways for migratory species, flows of sediments to downstream floodplains and deltas, areas of high freshwater biodiversity) (e.g., Hermoso et al. 2009; Winemiller et al. 2016; Worthington et al. 2022; Caldas et al. 2023). Tools and methods also exist for optimizing freshwater connectivity within a basin via the removal of specific barriers to achieve certain social or environmental objectives (Null and Lund 2012; Null et al. 2014; Hermoso et al. 2021; Garcia de Leaniz and O'Hanley 2022). These approaches have advanced significantly in recent years and provide decision-makers with the ability to make more informed decisions about which parts of the system are most strategic to restore or maintain connectivity.

Conclusion

We have presented here an array of measures that are currently possible for maintaining and restoring connectivity in the face of constructed barriers or other habitat alterations that impact freshwater connectivity. These measures span across the mitigation hierarchy from 1) avoidance, i.e., via avoiding barriers in the most harmful locations or via alternative options and/or via protections for critically important freshwater habitats from the impacts of built infrastructure, to 2) mitigation, i.e., mitigating impacts via barrier design or dam reoperation for environmental flows, to 3) restoration, i.e., via barrier removal. Although these measures provide a certain level of effectiveness, most have limitations in terms of fully reducing impacts on aquatic species and, thus, bending the curve for freshwater biodiversity. Moreover, there may be trade-offs involved, such as where removal of a barrier makes habitat accessible to invasive species (Rahel and McLaughlin 2018). As such, efforts to improve connectivity cannot be done in a vacuum without considering the ways in which interactions may occur with other threats and conservation measures.

It is apparent from the literature as well as conservation practice that we need better post-implementation monitoring to understand which measures work best under different locations, species assemblages, and other circumstances. For example, only 10% of over 37,000 river restoration projects in the US had implemented monitoring programs (Bernhardt et al. 2005). We do have decent evidence for some measures' effectiveness (e.g., removal of barriers shows clear improvements for certain species) and the limitations of others (e.g., ill-planned fishways designed only to move big salmon upstream). Knowing these limitations requires taking an evidence-based approach and avoiding the transfer of technology or solutions without local testing. To the extent possible, maintaining important connectivity corridors through good planning decisions is the best approach. The emerging efforts to identify "swimways" for migratory freshwater species will, for example, support a better understanding of where those corridors are critical for the viability of migratory species populations (Worthington et al. 2022).

While longitudinal connectivity is the most often recognized dimension of freshwater connectivity, the other three dimensions (lateral, vertical, and temporal/seasonal) are equally important. Measures that impact one dimension often will also benefit another, and, in some places, there will be synergies among actions taken (e.g., protection of headwaters may support downstream water quality and temporality of flows). In some locations, taking action to maintain or restore connectivity may be needed alongside other actions highlighted in this special issue.

Finally, we see the need for greater levels of innovation and expertise to support the development of new designs and a next generation of barriers that have minimal or no impacts on the connectivity of freshwater systems. Doing so will require interdisciplinary collaborations (e.g., among hydraulic engineers, limnologists, fluvial geomorphologists, and biologists) and an adaptive management framework with explicit monitoring components to inform future refinements. Dams that generate sufficient electricity or store water but are off channel, or at an existing, nonpassable waterfall, or only partially block a river channel, or are permeable to flows of aquatic biota and organic matter and levees that can be shifted in space over time, constitute the needed design challenge for the development of the next generation of technologies that can support bending the curve for freshwater biodiversity.

The "Field of Dreams Hypothesis" suggests that if we restore habitats, species will recolonize them (Palmer et al. 1997). As such, habitat restoration or protection can be viewed as a fundamental aspect of bending the curve for freshwater biodiversity. However, the ability to recolonize restored habitats depends on more than just the appropriate conditions being present; it also depends on the ability of organisms to get there. In this way, connectivity of freshwater systems is fundamental and co-equal with the other actions needed and presented in this special issue and introduced in Tickner et al. (2020) to support the recovery of freshwater species.

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Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Author information

Author ORCIDs

Michele Thieme https://orcid.org/0000-0003-3216-9129
Steven J. Cooke https://orcid.org/0000-0002-5407-0659

Author notes

Steven Cooke served as Advisory Board Member at the time of manuscript review and acceptance and did not handle peer review and editorial decisions regarding this manuscript.

Author contributions

Conceptualization: MT, KB, JJO, SJC
Data curation: AVV
Methodology: MT, SJC
Supervision: MT, SJC
Visualization: AVV
Writing – original draft: MT, KB, JJO, PAF, HR, LB, NN, KB, MS, GCO, RP, PT, SJC
Writing – review & editing: MT, KB, JJO, PAF, HR, LB, NN, KB, MS, PT, SJC

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