Dam Removal and River Restoration☆

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Glossary

Benthos Refers to the collective community of aquatic organisms that lives or forages at the bottom of an aquatic habitat like lakes, rivers, or the ocean.
Connectivity Represents the ability of water, organisms, and other materials to move among the main dimensions of a river, including longitudinally (upstream and downstream), laterally across the floodplain, and vertically through the interaction between surface water and ground water.
Dam removal mitigation A project, program, or structure designed to off-set the effects of dam removal, such as planting of vegetation, removal of exotic species, or installation of a water treatment facility.
Ecological memory The ability of past ecosystem states or events to influence present or future ecological condition.
Ecological response trajectory The path through time followed by an ecosystem or its fundamental properties after a major disturbance or restoration action.
Fish passage The modification or removal of barriers to allow fish and other aquatic organisms to swim and migrate unimpeded through a river system.
Instantaneous dam removal A dam removal project that proceeds following a relatively rapid drawdown (hours to days) of the impoundment.
Sedimentation The process of sediment transported in suspension by a river settling out once the water enters an impoundment, reservoir, or barrier.
Species turnover The change in taxonomic composition among habitats, time periods, or areas.
Staged dam removal A dam removal project that proceeds in stages, drawing out the reservoir drawdown by incrementally dismantling a dam.
Thermocline A relatively thin zone of stratification in a reservoir where layers contain markedly different water temperatures.

Introduction

We begin our discussion of dam removal by focusing on the importance of rivers. Rivers provide vital ecosystem services, largely through the provision of food, energy, and water. For millennia, humans have been attracted to rivers for these resources, settling near rivers and developing their floodplains. In the geologic record, signatures of human development on river systems date back to the earliest Mesopotamian civilizations of the 3rd millennium BCE, and elsewhere during the 1st and 2nd millennia BCE in Europe, Asia, and South America (Williams et al., 2014). Today, the intricate connections between societies and rivers occur across many socio-political boundaries and spatial scales. At the local scale (100s to 1000s of m^2) indigenous fishing communities harvest fish and use water for drinking and bathing; at continental scales, governments wrestle with river management—water scarcity, storage, irrigation, organic and inorganic pollution, eutrophication, disease, flood control, navigation, and sedimentation. Globally, rivers have sculpted the earth by weathering rock and mineral deposits, transporting sediment and nutrients to floodplains, river deltas, and oceans. They connect the atmosphere to the ocean via the water cycle and are a central geographic feature of many of the world's most populated cities.

Dams have become one of the most prevalent agents of change to the world's rivers. Early dam construction was largely driven by human needs for mechanical power, reliable water supplies, irrigation, and protection from floods, with little concern for the environmental consequences. As technology advanced in the modern industrial era, the form and magnitude of changes to rivers resulting from dam construction accelerated. The ability of human engineering to harness larger, more powerful rivers has advanced resulting in the damming of many of the world's rivers to maximize the provision of resources or infrastructure for providing flood protection, navigation, and recreational opportunities (Grill et al., 2019). Despite engineering feats that allow for the construction of mega-dams, the vast majority of the world's dams have heights of less than 10 m. Several national and global databases of larger dams exist (e.g., Mulligan et al., 2020), although the exact number of dams worldwide is unknown. Estimates using known databases of larger reservoirs and statistical projections of smaller reservoirs suggest that the number could exceed 16 million (Lehner et al., 2011). This number is expected to increase in the coming decades as developing countries build large dams on big rivers and small dams on tributaries for hydropower, irrigation, and water supply (Zarfl et al., 2015).

The different kinds of dams can be categorized into five groups (USSD, 2015). *Arch dams* are constructed of stone, brick, or concrete. They are curved in an upstream direction, which transmits the major part of force from the water load to the abutments (typically bedrock canyon walls or concrete). Arch dams facilitate a taller structure, which increases the reservoir storage capacity. A *buttress dam* is usually made of concrete, with a solid water-tight side upstream supported by concrete buttresses on the downstream side. A *gravity dam* depends upon its own weight for stability and can be constructed from concrete, stone masonry, timber cribs filled with rock, or roller-compacted concrete. An *embankment dam* is constructed of earth materials such as rock and soil, with an impervious core to control seepage. Finally, a *composite dam* consists of both embankment and concrete.

Effects of dams on rivers

Although dams produce societal benefits, they also impact the structure, function, and ecology of rivers and can have a range of impacts on indigenous communities both upstream and downstream of the dam structure. Dams instigate other potential socio-ecological impacts, such as population displacement, loss or inundation of agricultural lands, evaporative water loss, and greenhouse gas emissions. The ecological effects of dams occur both upstream and downstream of the structure; larger dams eliminate a free-flowing section of river by replacing it with a reservoir, while low-head dams may slow water velocities and create impoundments within the banks of the river channel. The magnitude of these effects depends upon the size of the dam and its impoundment, the operation and purpose of the dam, the geography and hydrology of the river system, and whether any additional drivers of change are present in the watershed, including other dams. Thus, each dam has a unique set of interacting factors contributing to the types and levels of impact on a river (Poff and Hart, 2002).

Immediately upstream of a dam, some of the free-flowing river is eliminated and replaced by an impoundment. The shallower and faster moving *lotic* habitat is replaced with deeper, slower moving *lentic* habitat. Although there may be some overlap, the organisms adapted to life in these two contrasting environments are different; therefore, creating an impoundment can cause a turnover in the assemblages of plant, invertebrate, and vertebrate species occurring in that segment of river. Reservoirs can also change the temperature regime of downstream waters. By absorbing more of the sun's heat and having a longer water residence time than an equivalent length of river, reservoirs can store heat. When water that passes through the dam originates from above the thermocline, the heated water can increase the temperature of waters downstream. In other cases, when the dam draws water from below the thermocline, a cooling effect can occur in downstream waters. In both cases, the change from the normal temperature regime can have consequences for downstream aquatic life. For dams without any provisions for fish passage past the dam (e.g., fish ladders, smolt bypass), migrating fish can no longer ascend or descend the river. This disruption of connectivity leads to loss of habitat availability, often extirpating upstream migratory fish and potentially leading to population declines across the whole river system.

Downstream of a dam, most of the changes to the river are driven by physical factors, which can indirectly affect organisms. A natural flow regime—defined by the magnitude of discharge, the timing and duration of peak flows, and the rate of change of flow events—determines the ecological character and integrity of a river (Poff et al., 1997). A river's natural flow regime is disrupted by dams when they are used to regulate discharge through water storage, withdrawals, and running turbines. Naturally occurring floods or pulses of seasonally high flows from snow melt, for example, that serve to reset the structure of gravel bars or create and transport large woody debris, may no longer occur with enough frequency or strength. Because many organisms are adapted to these habitat-forming processes and their timing, the effects on downstream organisms can cascade through freshwater food webs. In addition, the transport of sediment may be altered or eliminated, causing riverine habitat downstream to degrade and coarsen, which in turn affects the benthos and the ability of fish to spawn (Wohl et al., 2015).

A brief history of dam removal

As the effects of dams became more widely recognized and understood, the notion of deliberately removing them slowly emerged into the zeitgeist of river management and conservation. For much of human history, the removal of dams occurred unintentionally through failure during floods—whether due to old and degraded structures no longer able to withstand the forces of nature, or because new dams were improperly constructed or maintained. Such failures resulted in economic damage, environmental degradation, and in some tragic cases the loss of human life. Despite modern safety standards and monitoring, structural and catastrophic failure of dams still occurs, sometimes with lethal consequences.

The advent of dam safety regulations has helped propel the recent increase in dam removal. In some countries, modern safety standards, policies, and laws require regular inspections of dams to assess risk, resulting in the identification of deficient dams and potential candidates for removal. Some states and municipalities have dedicated funding to remove obsolete, unsafe, or hazardous dams. In other cases, especially for privately-owned dams, economics may cause owners to remove some dams when the return on investment is inadequate to justify costly repairs, upgrades, or other mitigation measures to resolve environmental effects and legal mandates (e.g., fishways for adult fish, trap-and-haul structures for juveniles).

Increasingly, river restoration has spurred dam removal because the return of a natural flow regime and increasing connectivity have repeatedly resulted in restoration of river functions (O'Connor et al., 2015). Sedimentation has also led to dam removals in cases where reservoir water storage capacity has been lost due to the accumulation of sediment. Largely propelled by these factors, dam removals in the U.S. have steadily grown in number since the mid-1970s (Foley et al., 2017). A comprehensive list of U.S. dam removals shows that as of 2019 about 1700 dams have been removed (American Rivers, 2020), while Europe has documented over 4900 barrier removals, many of them dams and weirs (Dam Removal Europe, 2020).

A large share of dams removed in the U.S. are small, generally less than 10 m in height. Based on available data, the median height of dams removed in the U.S. was ~3 m (Bellmore et al., 2017). The skew toward small dams in the size distribution of dam removals is driven by a suite of factors. There are many more small dams in the world than larger dams and they are, on average, older than large dams. Thus, in addition to being structurally deficient, their purpose is often tailored to a bygone era. Such small dams are now less likely to generate significant economic benefits compared with larger dams that store water or produce hydroelectricity, increasing their likelihood for removal. In contrast, the bias against larger dam removals stems from there being fewer of them; moreover, they are, on average, younger and are more likely to provide economic and societal benefits, although many are older than 50 years (Perera et al., 2021). Additionally, it is generally more arduous, time consuming, fraught with socio-economic challenges, and expensive to remove large dams and in some cases, like flood protection, to replace their function.

Not all dam removal projects fit neatly into the categories described above. There are exceptions, for example, to the prevalent small- versus large-dam rules of thumb associated with the reasons and primary cost drivers for dam removal decisions. Some low-head dams can impound large volumes of water, making their operational footprint considerable. Although the potential risks for property damage and loss of life associated with catastrophic failure are generally greater with larger dams, fatalities at hydraulically dangerous low-head dams (to swimmers, boaters, and other river recreationists) are also a public safety issue.

Considerations for dam removal

Several factors must be considered when evaluating potential dam removal projects. These can include legal requirements such as obtaining the necessary federal and local permits. Other practical issues surrounding project management include obtaining funding, identifying and getting input from stakeholders, and determining whether mitigation projects are necessary or required to minimize dam removal effects. Technical difficulty, expense, and time horizon of a proposed dam removal project contribute to its feasibility. Additional factors include whether the dam is publicly or privately owned, the purpose and size of the dam, level of reservoir sedimentation, the status and ecology of the river and surrounding project lands, the infrastructure downstream of the dam, and any necessary environmental compliance mandates. These all contribute to the complexity and unique scope of each dam removal project.

Existing manuals and technical documents provide recommendations for planning and conducting a dam removal project (e.g., Graber et al., 2015; USSD (U.S. Society on Dams Committee on Dam Decommissioning), 2015; Randle and Bountry, 2017; Georgia Aquatic Connectivity Team, 2020). For any given project, consultation with local experts and regulators who can provide information appropriately tailored to local conditions is prudent. Below, we briefly outline the main issues for consideration when scoping a dam removal project.

- *Assembling a project and stakeholder team*. Regardless of the scope and complexity of the dam removal project, planning will involve both the creation of a project team and engagement with stakeholders who have an interest in project details. A project team will be multidisciplinary and likely include a manager, engineers and restoration designers, biologist, geomorphologist, outreach specialist, and construction-engineering specialist. The main goal of a project team will be to define project objectives, obtain necessary funding and permits, conduct the removal and any necessary mitigation and post-project monitoring. Larger, more complex projects may require several intermediate steps, including feasibility studies, preliminary design analyzes, and alternative scenario plans (e.g., no action, refurbishing, rebuilding). There could be many potential stakeholders, including local, state, tribal, and federal agencies who have legal jurisdiction. Other parties—public utilities, business and industry groups, environmental and watershed groups, heritage and historical societies, indigenous communities and residents—also have an interest and differing viewpoints on how ecosystem services may be impacted by the dam removal project. The success of many dam removal projects has depended upon successfully navigating such complex socio-political relationships through the building of successful partnerships and institutional coordination (Johnson and Graber, 2002).

- *Determining the ownership of the dam and surrounding lands upstream and downstream of the project*. The potential ownership of dams spans a gamut of possibilities, from privately owned structures to those owned by local, state, or federal entities. In less common situations, older dams may have been abandoned, and their ownership is unclear or unknown.
- *Assembling historical and technical details about the dam and its structure*. These include obtaining information and technical drawings (i.e., "as-built plans") or photographs showing how the dam was constructed, the history of any modifications or rebuilds, and the materials used in the dam's construction. This key information (albeit often lacking for older structures) is helpful for planning the mechanical removal of the structure, especially for determining equipment needs and methods for removal. Additionally, other infrastructure associated with the project (e.g., roads, bridges, utility lines, water intake structures) or within the influence of the dam removal project area should be identified in the early stages of planning. This information is necessary for determining levels of risk from the dam removal and potential liabilities and mitigation needs.
- *Understanding project scope, including river hydrology and sedimentation.* Determining the amount of sedimentation and the concentration of possible contaminants is vital, as these factors are perhaps the most significant drivers of project cost, complexity, and the strategy for conducting a dam removal (Randle and Bountry, 2017). Such reconnaissance will set the boundaries of the sediment management planning and any mitigation measures required to protect downstream resources. The length and width of the reservoir, coupled with the characteristics of the stored sediments, play a role in predicting how much sediment will ultimately erode from the reservoir during and following dam removal (Major et al., 2017). Hydrological conditions of the river, including the magnitude and seasonal variability of flows and the hydraulic capacity of the river to erode the reservoir sediment are crucially important, as this will determine the rate of scour, deposition, and river channel evolution in the former reservoir area and downstream river channel (Doyle et al., 2002). Providing additional context to the issues of hydrology and sediment, detailed geomorphological assessments upstream and downstream of the dam, including cross-section surveys and longitudinal profiles, can be vital for project planning.
- *Identifying needs for infrastructure and species protection.* Assessing the potential impacts to infrastructure or biological species of special concern within the project area is necessary, as this will influence the planning, permitting and conduct of the dam removal project. Many of the concerns surrounding infrastructure are focused upon how reservoir drawdown and sediment release will impact the function of existing water-related infrastructure. For example, development of reservoir shorelines can follow construction of a dam, creating infrastructure like wells, surface-water intake pipes, and septic systems. Once a reservoir is drained, concerns arise for this infrastructure. In their review of this topic, Tullos et al. (2016) noted that the effects of dam removal on wells were dependent upon whether the water table was hydraulically connected to the reservoir. For many locales, existing databases indicate the potential presence of sensitive aquatic species, including plants, fish, amphibians, invertebrates, and mammals, but additional local-scale surveys for potentially impacted taxa of concern may be necessary. For cases where sensitive species are present, actions may be required to reduce or eliminate potential negative effects. These include scheduling dam removal activities to avoid biologically sensitive times of year, utilizing abatement strategies to minimize noise from construction equipment, and relocating sensitive sessile and mobile animals from the project area into safer habitats.
- *Identifying regulatory statutes and environmental compliance mandates*. This includes obtaining the necessary permits to conduct the dam removal. Requirements vary among jurisdictions and consulting with local experts would be beneficial. In the United States, federal regulations that may apply to a dam removal project might include: (1) the Clean Water Act (Sections 401, 402, and 404) to protect water quality and regulate the discharge of dredged or fill material into navigable waters of the United States (administered by the U.S. Army Corps of Engineers and Environmental Protection Agency); (2) the Endangered Species Act (administered by either the National Marine Fisheries Service or the U.S. Fish and Wildlife Service); (3) the Magnuson-Stevens Act if commercial fish species are present in the project area, and (4) the Federal Power Act, which gives the Federal Energy Regulatory Commission (FERC) the exclusive authority to license non-federal hydropower projects. Some dams are designated as historical or culturally significant sites and may be protected by laws like the National Historic Preservation Act. State and local regulations may also apply.

Case-studies and conducting a dam removal

Once permitting and other logistical preparations are completed, the deconstruction phase of dam removal can proceed following one of three possible pathways—partial dam removal, instantaneous dam removal (also referred to as "sudden") or staged ("phased") dam removal. These pathways differ in the rate and extent of removing the structure from the river (given the needs and constraints of the project, as described above) and determine the time horizon of the project.

A partial dam removal is applied in cases where logistical (e.g., sediment retention) or socio-political (e.g., dam is a historically significant site) factors call for retention of some portion of the dam. For example, the portion of a dam blocking fish passage might be removed while other portions of the dam and related structures are left in place for historical preservation. Three different case-studies highlight the different factors that might lead to a partial dam removal. The first example involves the Kent Dam on the Middle Cuyahoga River in Ohio, where significant water quality degradation was caused by a dam no longer serving its intended purpose. Dam removal was considered necessary to improve the water quality status of the river. Yet, the historically significant dam was one of the oldest arch masonry dams in the U.S. and by creating a picturesque waterfall it was a culturally important feature for the citizenry (Tuckerman and Zawiski, 2007). A compromise was reached where a partial dam removal allowed part of the dam and its waterfall to be retained, while a bypass channel reconnecting the downstream and upstream portions of the river improved water quality.

A second example of a partial removal comes from Banff National Park in Canada. In this case, the town of Banff dug wells, thus negating the 8-m high water-storage dam's primary purpose, even as it remained a liability requiring costly annual maintenance and inspections. A flood washing out the dam's access road led to proposals for dam removal, but due to funding limitations the town managers decided to pursue a partial dam removal where only a portion of the dam was removed, but a bypass channel was engineered with both concrete and natural substrate that allowed fish passage (Sullivan et al., 2019). This was particularly beneficial for bull trout (*Salvelinus confluentus*), a protected migratory species in the province.

The final example of a partial removal comes from Taiwan, where a series of sediment retention check dams were limiting the available migration corridor of the land-locked Formosan salmon (*Oncorhynchus masou formosanus*). The most downstream and largest dam (Number 1 Dam, 16 m) on the Chichiawan River was slated for removal to increase connectivity for the last remaining population of this critically endangered fish species (Chang et al., 2017). Project planning identified that a main road would be impacted by full removal of the dam, but a partial removal allowed the western abutment to remain and protect the road while still restoring fish passage.

Full dam removals are cases where the dam is removed, the stream bed is returned to its original elevation and course, and all portions of the dam that could influence hydrological conditions of the river are removed. A full dam removal can be accomplished in two ways, differentiated mainly by the speed of the removal process and the rate of reservoir drawdown. In an instantaneous dam removal, reservoir draw down occurs in a matter of hours to days. Some of these projects are informally described as "blow and go," where a portion of the dam is first removed, sometimes with explosives, so that rapid and complete draining of the reservoir follows. Such instantaneous dam removal using explosives occurred with the 38-m high Condit Dam, on Washington State's White Salmon River, where a detonation of explosives in a tunnel bored out of the bottom of the dam caused a rapid and complete drawdown of the reservoir, releasing a large volume of sediment downstream. This minimized the duration of high sediment concentration experienced by fish populations downstream of the dam, limiting impact to a single spawning season instead of multiple seasons (as in some phased removals, see below). After the breach, the remains of the dam were mechanically removed in stages over the next 12 months. Note however that for smaller dams a rapid reservoir drawdown is usually achieved with more conventional methods using construction equipment.

A second type of full dam removal is staged dam removal which, by design, is drawn out over months or years. This is a method often used for taller dams where large amounts of sediment are contained within the reservoir, raising environmental or infrastructure concerns for accepting waters downstream. A staged removal allows the pace of reservoir drawdown to be controlled, which is a major determinant of the rate and timing of sediment mobilization. By maintaining the reservoir as the dam is removed in stages, the project managers can retain some level of control over the timing, duration, and amount of sediment released downstream. It also gives time for erosive processes and lateral channel migration to mobilize and redistribute sediment within the reservoir. Factors such as the presence of sensitive species and infrastructure, or a limited capacity of the receiving channel downstream to accept sediment, can initiate the need for a staged dam removal.

A good example of a staged dam removal comes from the Elwha River in Washington, where two dams were removed using two different staged dam removal strategies. The downstream Elwha Dam was a 32-m tall concrete gravity dam. Its staged removal was accomplished by alternating the river's flow through one of two constructed channels, using temporary coffer dams to route water through one channel at a time. The second dry channel was excavated to a lower elevation than the one with water, so that when the flow was switched between channels, the elevation of the reservoir was reduced by an amount equivalent to the difference in elevation between the wet and dry channels. A total of 10 channel switching events were used to remove the dam over an 8-month period. The taller 64-m Glines Canyon Dam was a concrete arch dam with a reservoir that contained about 75% of the 21 million m^3 of stored sediment contained behind both dams (Randle et al., 2015). Gradual removal of this dam was accomplished over a three-year period by notching the dam, at first mechanically with hydraulic hammers and then with explosives. The depth of each notch reduced the water elevation of the reservoir to a set amount, determined by limits of reservoir slope stability and levels of sediment to be released downstream to minimize negative effects to fish and their habitats. This incremental workflow also enabled project managers to control and manage sediment within the former reservoir, allowing the river time to erode, deposit, and redistribute sediment within the former reservoir.

Alternatives to the strategy of river erosion may be required when sediment cannot be released downstream. Removal of sediment, via dredging or mechanical removal, can minimize the downstream impacts or mitigate issues with contaminated sediments. However, this usually dramatically increases project cost because in addition to sediment dredging, project planners must find a location to dispose of the material and a method for transport. Mechanical sediment removal strategies were required to remove contaminated sediment stored behind the Milltown Dam on the Clark Fork River in Montana, a U.S. Superfund site, before dam removal could proceed (Brooks, 2015). In the case of the 32-m tall San Clemente Dam on the Carmel River in California, the aging dam was a safety risk, with a reservoir filled to 95% of its capacity with sediment. Dam removal was necessary, but the stored sediments posed a sediment management dilemma because downstream development, infrastructure, and limited channel capacity imposed unacceptable risks from a large sediment release. The creative solution involved leaving the reservoir sediments in place and constructing a bypass channel to reroute the river around the former reservoir reach. This approach allowed for sediment transport from river reaches upstream of the reservoir while sequestering reservoir sediment that may have created downstream issues for roads, houses, and other infrastructure (Harrison et al., 2018).

Physical and ecological outcomes of dam removal

As the number of dismantled dams has grown, the scientific community has increasingly studied the outcomes of dam removal (Table 1), including whether the environmental changes caused by dams can be reversed. Nearly 10% of the dams removed in the U.S. have been scientifically evaluated, through assessing changes to a suite of physical, water quality, and biological variables (Bellmore et al., 2017). Although many studies collect before and after dam removal data, some only collect post-removal data. Most of these studies, no matter their experimental design, have lasted for relatively short durations, and they have evaluated outcomes for a few years around the initiation of dam removal. Long-term evaluations are rare, as most studies have focused upon the time period where rapid physical changes take place in the upstream and downstream vicinity of the dam. As the number of case studies evaluating river outcomes has increased, synthesis of the physical and ecological responses has emerged alongside tools like numerical hydrodynamic and sediment modeling to allow predictions about how a river's condition will change over time following dam removal.

When conceptualizing responses to dam removal, it is helpful to segregate—in both space and time—the processes that affect the structure and function of the river ecosystem (Hart et al., 2002; Bellmore et al., 2019). Spatially, the most straight forward case involves a single dam that effectively creates three distinct zones that behave differently following dam removal. These zones are the river segment upstream of the reservoir, the reservoir section from the river inlet to the dam, and the reach downstream of the dam. Within each of these spatial domains, different sets of physical and biological factors and processes drive change, which collectively impact the shape of the ecological response trajectory following dam removal. This trajectory is also shaped by differences in temporal dynamics, as both short-term and long-term responses are dependent upon a suite of factors, including the size of the dams, amount of sediment, and ecological context (Fig. 1).

Changes to the upstream spatial domain are driven by restoration of connectivity following dam removal. The ability of organisms to travel past the dam location into upstream waters can increase species richness and life history diversity. This is especially true for migratory fish populations, which can be lost from upstream reaches following the placement of a dam unless significant mitigation (e.g., fish ladders for adults to pass the dam) is taken. Once passage is returned following dam removal, migratory fish from reaches downstream of the dam can swim up past the former dam, often rapidly repopulating upstream reaches, which over time can increase upstream species richness (Wippelhauser, 2021). Given the right conditions, in terms of environmental suitability and genetic memory, life-history diversity can re-emerge in upstream populations. This was seen when summer run Steelhead (*O. mykiss*) that were rare for decades prior to dam removal returned to the Elwha River following dam removal (Fraik et al., 2021). The return of fish to upstream reaches can also drive changes indirectly, as seen when Pacific Salmon (*Oncorhynchus* spp.) provide marine-derived nutrients to their freshwater spawning grounds. These marine-derived nutrients can be seen in both aquatic and terrestrial food webs (Tonra et al., 2015). Salmon can also transport freshwater mussel larvae to upstream areas and significantly alter the stream benthos through bioturbation disturbance from their spawning activity. A potential downside to restored connectivity occurs in cases where significant risk exists from invasive species migrating into upstream waters. This has deterred some potential dam removals, such as in streams draining into the Great Lakes in the U.S., where significant resources are directed toward eliminating Sea Lamprey (*Petromyzon marinus*), which spawn in rivers and as adults parasitize commercially important fish species in the lakes (Jensen and Jones, 2018).

The most dramatic changes to physical, biological, and ecological factors occur in the former reservoir reach. This spatial domain experiences a wholesale change from a lake-like (lentic) ecosystem to a river ecosystem (lotic). Once a dam is removed, the reservoir drains, stored sediment is transported downstream, and a new channel emerges within the former lakebed. Initially, the re-emergent river channel (or braided channels in wide reservoirs) is unstable. As the sediment interacts with hydrological flows, a stable channel will eventually reform. The pace of this physical transformation varies, depending on the size of the impoundment, stored sediment volume, and hydrological conditions. As the river channel reforms, the aquatic communities adapted to pelagic conditions and lentic fish species are replaced by benthic production and lotic fish species. For some systems, such species turnover can be considerable, but the absolute number of species may not change, and some generalist species can be found in the same area before and after dam removal (Bellmore et al., 2019). A driving force that determines the reassembly of species following dam removal is the "ecological memory" of the system, defined here as the current and future influence of the cumulative past impacts to

Table 1 Case studies with key citations illustrating some of the concepts of dam removal discussed in this chapter.

Name of site	*Country*	*Main topic/concept*	*Key citations*
Elwha River (Elwha + Glines Canyon dams)	Washington, United States	Large-staged dam removal	Ritchie et al. (2018)
		Multi-dam project	Duda et al. (2020)
		Reservoir sedimentation	East et al. (2015)
		Fish passage	
Sandy River (Marmot Dam)	Oregon, United States	Large-instantaneous dam removal	Major et al. (2012)
		Sediment transport	Cui et al. (2014)
Clark Fork River (Milltown Dam)	Montana, United States	Contaminated sediment	Woelfle-Erskine et al. (2012)
		Downstream geomorphology	Evans and Wilcox (2013)
			Brooks (2015)
Kaoshan Steam (Kaoshan I-IV)	Shei-Pa N.P., Taiwan	Multi-dam project	Battle et al. (2020)
		Fish passage	Chang et al. (2017)

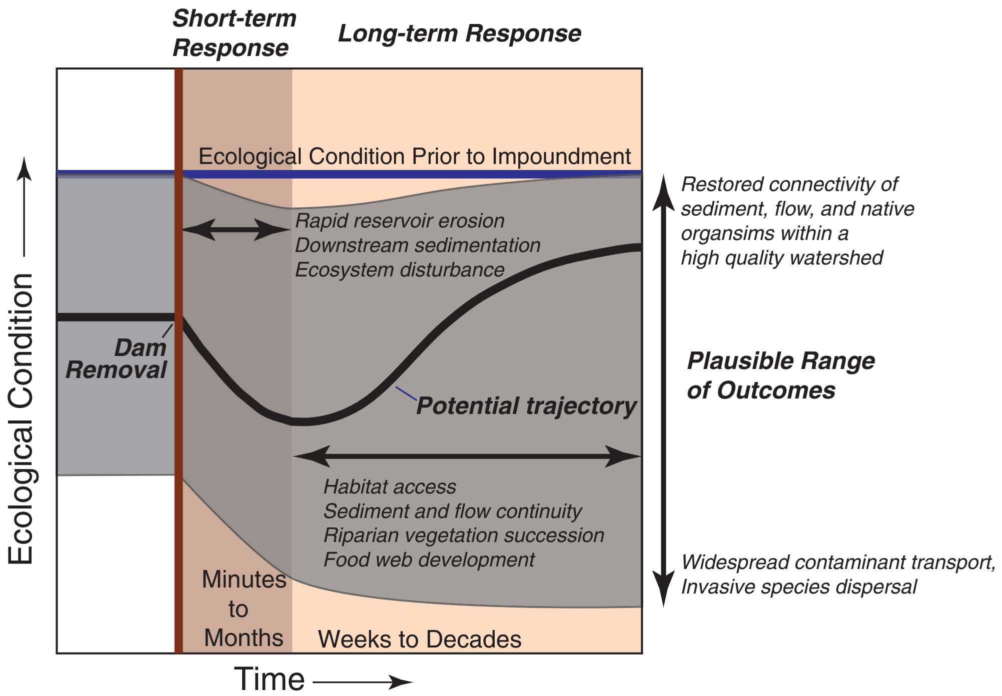

Fig. 1 Conceptual model of the ecological trajectory of a river following dam removal. Considerable variability exists in the condition of the river prior to removal (gray area to the left of the dam removal line). Following the initiation of dam removal, a short-term disturbance effect is caused by the dam removal, but conditions improve in the long-term as natural flow and sediment regimes are restored and habitat access in the former reservoir and upstream areas is resumed. A range of plausible outcomes (gray area to the right of the dam removal line) exists due to a suite of possible factors influencing the river condition outcome, such as existing watershed condition, size of the dam and sediment released, and strategy of dam removal From Foley MM, Bellmore JR, O'Connor JE, Duda JJ, East AE, Grant GE, Anderson CW, Bountry JA, Collins MJ, Connolly PJ and Craig LS (2017) Dam removal: Listening in. *Water Resources Research* 53: 5229–5246. Used with permission.

the ecosystem. In cases where upstream, downstream, and tributary reaches retain a high level of species and life history forms available for repopulating the reservoir reach, the system will more closely approach the pre-dam condition. Conversely, if these species and life history pools are diminished, due to the age of the dam or via other disturbances in the watershed, the river ecosystem might not approach the state that existed prior to dam placement (see Fig. 1). Natural revegetation within riparian and upland zones, sometimes assisted by seeding and planting, further stabilizes former reservoir surfaces, over time reducing erosion. With the return of riparian and upland vegetation, wildlife species also return and can further assist in normalizing habitat structure and function, as well as re-establishing trophic ecological interactions within the former reservoir reach.

Downstream of the dam, changes to the river are driven by fluxes of water, sediment, organic material, and nutrients caused by the dam removal. As the reservoir base level declines, either rapidly or in stages, fine sediments from the reservoir are eroded and transported downstream, even with modest river flows. Much depends on the amount of sediment stored in the reservoir, the characteristics of the sediment (e.g., bulk density, grain size), frequency and magnitude of floods, and the characteristics of downstream river reaches that are receiving and transporting the sediment (Major et al., 2017). Given the wide range of sediment volumes and dam conditions previously observed, a common theme among dam removal projects is that even large changes in geomorphology are relatively short-lived. A river will process the stored sediment, sometimes in amounts that are multiples of the river's naturally occurring annual sediment load, by transporting it downstream. Temporary changes in elevation, channel morphology, and grain size of the stream bed will occur. Over time, as supply from the reservoir diminishes to background levels, an equilibrium condition will emerge in the downstream reach to the point that the river channel approaches the pre-dam condition. From a physical standpoint, most rivers are resilient to the dam removal disturbance and largely recover their form and function soon after dam removal (Magilligan et al., 2021).

The downstream response of individual species, biological assemblages, and their trophic structure are also impacted by perturbations brought about by dam removal (Lake et al., 2007). The fluxes of water and sediment can have both direct and indirect effects on aquatic and riparian organisms, as well as significantly altering or entirely removing their habitats, at least for a time after the initial sediment pulse. Again, context—in terms of the size of the dam, amount of sediment released, dam removal strategy, and how altered the downstream ecosystem is from its pre-dam condition—matters (Foley et al., 2017; Bellmore et al., 2019). Burial of the benthos by sediment can directly impact organisms, particularly sessile organisms that cannot disperse to other less impacted areas. It is typical to see a rapid change in the species assemblage and the density of aquatic macroinvertebrates following dam removal (Carlson et al., 2018), with species tolerant of finer sediments and scour favored over sensitive taxa intolerant of such conditions. Also, sediment release usually increases the turbidity of the river, which reduces light availability and can affect the taxonomic composition of benthic primary producers and their capacity for production. Reductions in the densities of benthic algae and invertebrate communities have been widely reported and are usually most significant in the reaches closer to the removed dam. These changes are often temporary, with recovery occurring once the dam removal effects diminish. Fish have been shown to be less directly impacted by sediment release from dam removal than organisms of the benthos, although mortality and damage to gills from abrasion are possible. Unlike sessile organisms or those with narrow habitat requirements, many fish species can avoid or move to refuges to escape the highest impacts associated with dam removal. Yet, indirect effects can affect fish and their habitats. A reduced food supply from reductions in benthic production, a diminished capacity to visually forage in high turbidity conditions, and diminished suitability of spawning habitat can all lead to decreased fitness of individual fish and reductions in population size during and following dam removal as the river processes the physical changes (Stanley and Doyle, 2003).

Despite the short-term disturbance caused by dam removal, a growing body of research suggests that rivers, given the opportunity, can recover substantially from having been dammed. However, the structure and function of the ecosystem may not be the same as what existed prior to dam emplacement. Changes in ecological communities caused by dams, such as extirpation of native species and harboring of invasive species, can limit the capacity for the ecosystem to reassemble into the pre-dam condition following dam removal (see Fig. 1). Moreover, land use, the presence of other dams, sediment contamination, climate change, and numerous other factors may constrain both physical and ecological trajectories. The ability to go back to a pre-dammed state will likely depend on how long the dam existed and the magnitude of its many-faceted effects on the ecosystem. Even if all elements of the ecosystem still exist, it is unlikely they will reassemble in the exact fashion that existed previously.

Future outlook of dam removal

It is likely that the number of dam removals and communities removing dams will increase into the future, for both practical and aspirational reasons. Given the immense number of dams and their age, there will be a number of candidates for removal, particularly dams that have aged beyond repair and outlived their usefulness. In places where the practice is well established, these dams (especially smaller dams) will continue to come down, probably with greater efficiency and less controversy. In regions or countries with few dam removals, translating the knowledge and experience gained from past projects could lessen the learning curve and institutional barriers to applying the practice where applicable. Coupling predictions about expected outcomes with a wide range of experience in conducting dam removal should see dam removal emerge as an accepted practice in areas where it is currently rare, especially when applied to dams that are beyond repair or pose a significant risk to life and property.

The opportunity to build on past successes and intensify river restoration efforts is gaining momentum, in terms of scientific expertise, practical experience, and public policy. This has led to a reassessment of policies and practices involved with the management of rivers. As an example, a recent joint statement from a working group representing the U.S. hydropower industry and the environmental and river restoration community recognized the need to remove dams that, "no longer provide benefits to society, have safety issues that cannot be cost-effectively mitigated, or have adverse environmental impacts that cannot be effectively addressed" (U.S. Hydropower: Climate Solution and Conservation Challenge 2020). The statement also acknowledges that hydropower is an important component of renewable energy strategies and that rehabilitating and retrofitting existing dams will also be important tools for addressing the myriad of challenges facing the wise use and conservation of the world's rivers.

Knowledge gaps

Considerable progress has been made in the field of dam removal over the last three decades. The action of physically removing a dam from particular river is a relatively straight forward construction-engineering process. Yet, additional knowledge and advances in key areas are still needed, largely in decision making and predicting the long-term outcomes of individual dam removal projects.

- Decision making
  - Prioritization and optimization tools to aid decision making and selecting dam removal projects.
  - Numerical modeling, in particular for tracking the fate of stored sediment and ecological outcomes.
  - Tools for estimating the cost of dam removal projects.
- Outcomes of dam removal
  - Assessing cumulative impacts of removing multiple dams from a single watershed.
  - Long-term outcomes of river response and restoration
  - Quantifying socio-economic effects, such as long-term outcomes to property values, economic trajectories of communities near dam removal projects (e.g., recreation, commercial fishing), cultural resurgence of indigenous peoples, communities, and river economies, as well as other societal benefits.

Conclusion/Synthesis

Dam removal is an important tool for river restoration and addressing aging infrastructure. It is an ongoing activity that will continue as a large number of aging dams that are no longer serving their original purposes, have become safety liabilities, or represent potential for significant restoration action are taken down. The increase in the number of dams removed has led to a greater understanding about the outcomes to the river and its ecosystem. Rivers are resilient to the changes and disturbance that accompany the removal of a dam, with many of the changes occurring rapidly and representing an improvement in water quality, hydrological flows, and migratory movement of aquatic animals. Yet, some of the outcomes of dam removal may play out over longer time periods, depending on such factors as the life-history of key species or implementation of other complementary river restoration actions. In the future, as societies are faced with changing hydrologic and land-use drivers that influence water use and conservation, dam removal will be an important option for maintaining or enhancing the values and ecosystem services of the world's rivers.

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