BARRIER REMOVAL IS A STRATEGY FOR CLIMATE RESILIENCE

JULY 2025

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EXECUTIVE SUMMARY

Millions of dams and in-stream barriers have been built worldwide to manage water supply, reduce flood risk, generate hydropower, and support recreation, navigation, and road infrastructure. The National Aquatic Barrier Inventory estimates over 550,000 dams and over 298,000 road-related barriers that fragment streams in the United States[1]. As dams age and as droughts and floods become more intense, some dams and barriers have become problems, for example, by outliving their useful life, presenting safety concerns to communities, and impacting ecosystems, especially in a changing climate. These dams – the ones that present safety concerns due to their age and deferred maintenance – should be considered candidates for removal as a strategy for climate resilience and to help communities prepare for and respond to increasingly volatile weather.

Climate change has created increasingly volatile weather over the past century, resulting in more frequent drought, catastrophic flooding events, and warming water temperatures[2]. Warmer air temperatures increase the atmosphere's capacity to draw moisture, leading some streams to dry seasonally, more water to evaporate from reservoirs, and irrigation demands to increase. Warming temperatures are also shifting precipitation from snow to rain, yielding more winter runoff earlier in the season when water is a hazard, and a longer dry season when water is a needed resource. Drier conditions raise the risk of severe fires, which can eliminate vegetation, causing erosion that deposits sediment in rivers and reservoirs. In dammed river systems, this sediment builds up in reservoirs, where it decreases reservoir depth and reduces water storage capacity – overall, decreasing water availability for beneficial uses, such as habitat maintenance, drinking water, and crop irrigation.

The changing climate is also intensifying storms, bringing more extreme precipitation patterns that swing between drought and deluge, heightening flood risk. This climate change-related threat alters the cost-benefit of maintaining dams and barriers, by: (1) reducing dam utility and benefits; and (2) presenting the need for dam retrofits to avoid failure, sustain aquatic ecosystems, and protect communities downstream of dams.

Most dam construction in the United States occurred prior to 1980. These aging dams were designed and constructed to withstand the largest predicted storm flows in the dam's watershed at the date of construction. As a result of changing precipitation patterns, many of these dams cannot withstand current and expected storm conditions, affecting water management and dam safety. Such dams must be modified to avoid failure or will risk harm to downstream communities. Needed retrofits are often expensive, with dam removal costing approximately 30-40% of the retrofit price tag[3]. In many instances, dam owners are unable to generate funding for the necessary safety modifications, as dam utility (e.g., revenue from hydropower generation and water sales) decreases.

[1] As of March 2025, 554,420 dams and 298,609 road-related barriers that impact aquatic organisms have been identified by the National Aquatic Barrier Inventory.

[2] Stevenson et al. 2022 describe changes to extreme weather in the 21st Century.

[3] Massachusetts Dept of Fish and Game found that removing 3 dams was 60% less expensive than repair and maintenance over 30 years. Habel et al. 2020 estimate that removing structurally deficient, high hazard dams is 10-30 times less expensive than rehabilitating them.

In summary, climate change alters the benefits of dams, including by reducing reservoir inflows for water storage and hydropower generation during droughts, while complicating flood management utility as storms intensify. Removing aging, unsafe, and obsolete dams before anticipated climate volatility occurs helps communities better prepare for future fluctuations between wet and dry conditions, while avoiding some of the worst impacts from such events. In other words, in some instances dam removal is a multi-benefit and cost-effective solution to help communities become climate resilient.

KEY FINDINGS FOR IMPROVING CLIMATE RESILIENCE BY REMOVING DAMS AND STREAM BARRIERS

1. Nature-based solutions, including removal of dams and stream barriers, help strengthen resilience to increasingly volatile weather by allowing natural processes to adjust to and recover from extreme weather events.

2. Dam removal reconnects rivers, sediment fluxes, habitats, and fish and wildlife populations, which all have widespread benefits for climate resilience.

3. As air temperature warms, removing dams and barriers is an effective way to provide access to cooler water for fish and other wildlife.

4. As storms become more intense, removing unsafe, aging, and obsolete dams and barriers will improve human safety.

5. Dams and stream barriers have already been removed to bolster resilience to more frequent and severe droughts and floods.

6. Measuring resilience to volatile weather for barrier removal can be as straightforward as counting connected river area for flood flows, but may also be more specific, depending on climate resilience goals.

7. Every river system is unique, so there is no one-size-fits-all approach to improve and measure climate resilience.

8. A resilient future will likely combine nature-based solutions that support healthy river systems, with built infrastructure to provide benefits like flood protection and water supply.

INTRODUCTION

Communities are removing dams for a variety of reasons, including safety, economics, and environmental protection. In the US, 2,215 dams and barriers were removed between 1912 and December 2024, with 83% of removals taking place since 2000[4]. These removals include mostly small dams and barriers that outlived their useful life, and a few large, highly visible dam removals, such as the Bloede Dam in Maryland, Elwha Dam in Washington, and the Klamath dams in California and Oregon.

Communities led many of these dam removals as a strategy to build resilience to changing climate conditions. The National Oceanic and Atmospheric Administration (NOAA) defines climate resilience as the ability to prepare for, respond to, and recover from adverse events related to climate change. Removing obsolete dams and barriers shows promise as a nature-based solution to adapt to climate change, such as more frequent droughts and floods (Figure 1).

For instance, removing dams resolves the threat of dam failure to communities living downstream of dams. The average age of US dams is 64 years[5]. Aging dams – and especially dams that are not properly maintained – are becoming increasingly dangerous as stream flows exceed design specifications, heightening the risk of dam failure[6]. Dam failures and near misses that endangered communities have occurred throughout the country, including in Vermont, California, Michigan, North Carolina.

[4] American Rivers' dam removal database (Version Feb2024).

[5] According to the National Inventory of Dams, which uses a database of more than 92,000 dams. Dams are included in the database if they are over 25 feet high with at least 15 acre-feet of storage, or over 6 feet high with at least 50 acre-feet of storage.

[6] See Vahedifard et al. 2021 for more background on aging dams and changing streamflows.

TERMS AND DEFINITIONS

Adaptation = The process of adjusting to a novel climate and its effects. Human intervention may facilitate adjustment to expected climate and its effects.

Nature-based solutions = Natural landscapes managed to provide both ecological and societal benefits by allowing for dynamic, natural processes.

Obsolete dams = Instream structures that no longer serve their purpose and are relics from earlier water management priorities.

Climate resilience = The ability to prepare for, respond to, and recover from adverse events related to climate change.

Unsafe dams = Aging infrastructure and extreme storm events increase the risk of dam failure.

Removing obsolete dams also benefits fisheries, which are often culturally and economically beneficial for recreation and commercial fishing opportunities that provide healthy high-value food sources. Dam removals can reconnect river systems, providing aquatic organisms with improved access to more complex, and cooler habitats, bolstering their resilience against stream drying, warming stream temperatures, and sedimentation following severe wildfire.

Overall, dam removal practitioners are increasingly identifying climate resilience as a reason to remove dams, for both human safety and species survival[7].

[7] Abbott et al. 2024 provide dam removal practitioners' perspectives on incorporating climate change into restoration decisions.

CLIMATE CHANGE ALTERS THE BENEFITS AND RISK OF DAMS

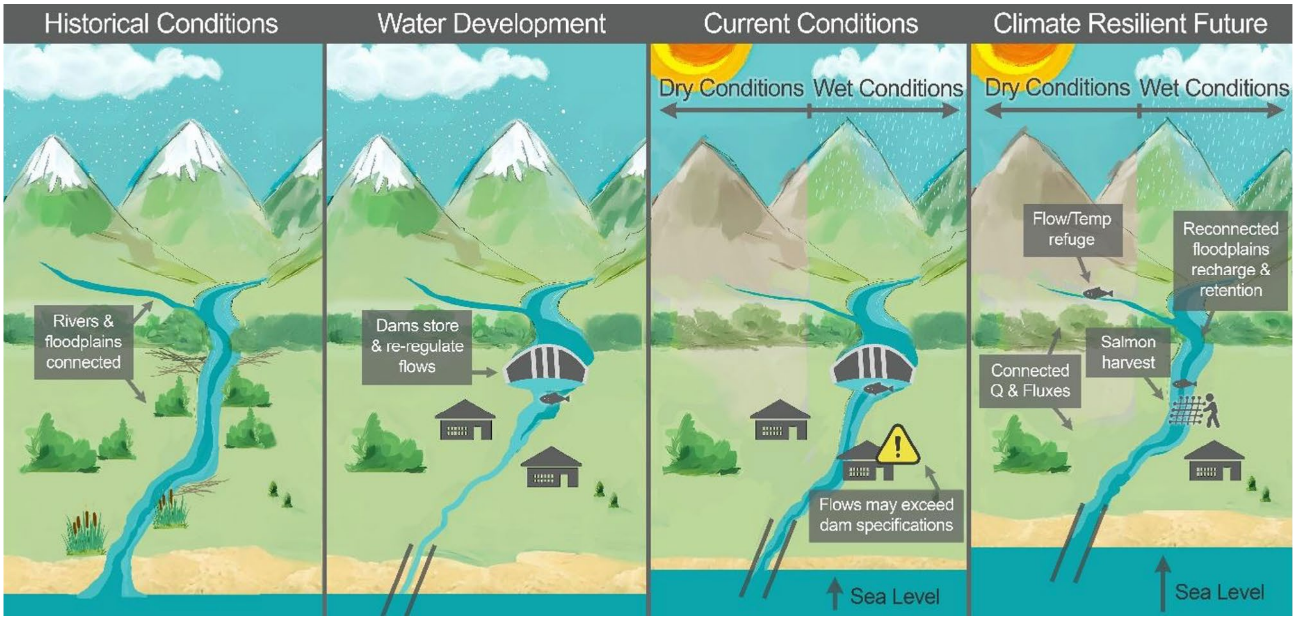

FIGURE 1. *1st panel: Historical conditions for which dams and barriers were designed, with water stored in snowpack and less variation between low flows (dark blue) and high flows (light blue). 2nd panel: Conditions following dam development with fragmented rivers, altered streamflows, and water stored in snowpack. 3rd panel: Current conditions when unpredictable rainfall-driven streamflows have caused some dams to be obsolete or unsafe, and sediment buildup in reservoirs exacerbates flood risks for coastal communities facing rising sea levels. 4th panel: A social and ecological climate resilient future with obsolete barriers removed, enabling aquatic species to access headwater streams, cultural and nature-based connections to be reintroduced, and water and sediment to flow downstream for safer communities.*

LITERATURE REVIEW OF DAM REMOVAL AND CLIMATE RESILIENCE

Most dam removal studies focus on the environmental harm of dams and potential river restoration benefits of removing them[8]. For example, sediment that reduces reservoir capacity often erodes quickly following dam removal. In addition, dam removal can restore river processes and re-establish a river's natural temperature range, which is frequently colder than water in a reservoir. Fish tend to respond to re-connected rivers by re-establishing populations in upstream reaches, although these ecological responses to dam removal are slower than physical responses, such as sediment movement. However, there is a good deal of variability between dam removal projects, including their locations, river and dam sizes, and ecological communities. Despite the focus of dam removals on environmental response, these studies often fall short of explaining the connection between dam removal and climate resilience.

[8] Foley et al. 2017 synthesize dam removal and river restoration studies.

To find out if removing dams is a strategy for enhancing climate resilience, we reviewed an extensive body of scientific reports and publications. Our assessment of climate resilience benefits was broad, encompassing social (human safety, economic, cultural) and environmental (connectivity, biological, physical/chemical) criteria. Studies included post-dam removal monitoring, dam/barrier removal modeling, risk analyses, perspectives, meta-analyses, and more.

We identified 50 studies, published from 2009 through September 2024, that examine dam removal in relation to climate change, resilience, or adaptation. Although the relationship between dam removal and climate resilience remains under-studied, it is clear that removing dams is broadly beneficial as a climate resilience approach.

Our research found the most robust evidence of improvement for: community safety, river connectivity, healthy fisheries, and stream temperature, all of which benefit climate resilience (Figure 2). Below, we detail how dam removal augments climate resilience for these and other important societal and environmental benefits.

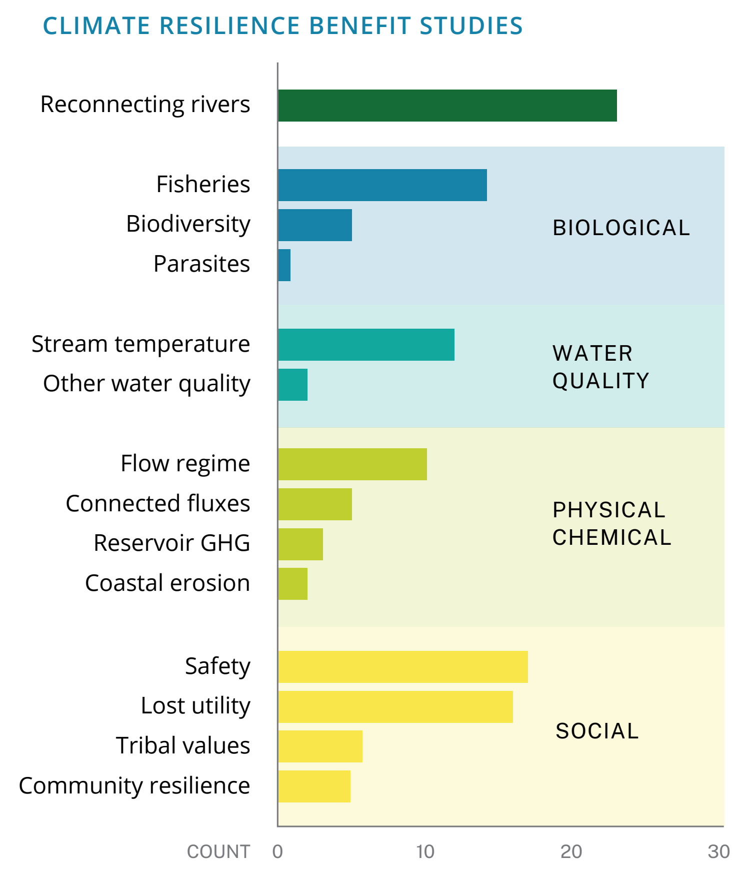

FIGURE 2. *Number of studies that identify climate resilience benefits of removing dams or barriers. Some studies discuss multiple climate resilience benefits.*

Removing outdated dams to create safe, resilient communities

Removing dams and barriers enhances human health and safety in the context of climate threats. In particular, protecting communities from dam failure and ensuing floods is a serious concern as more extreme storms result in floods that exceed the physical and operational standards of aging dams. By removing dams, we help communities downstream of barriers avoid the frequently devastating impacts of flood-related dam failure.

The National Inventory of Dams (NID), which tracks the condition of the nation's largest dams, reports close to 85% of these dams are in less than satisfactory condition, and 13% are high hazard dams that present a risk to people living downstream[9]. Many of these dams have outlived their life expectancy and pose a growing risk to housing and infrastructure downstream of dams. The number of dams considered to pose a high risk to human life has risen from 10,185 dams in 2008 (about 11% or all dams in the NID database) to 16,745 (about 18% of add dams in the NID database) by 2025[10]. This change is primarily from urban development downstream of dams.

According to the ASDSO Dam Incident Database, recorded incidents of dam failures and emergency interventions to prevent imminent failure have risen sharply over the last two decades[11]. From 1900-1999, there were an average of two dam incidents per year. The recorded figures increased significantly beginning in 2000 with an average of 10 incidents per year from 2000 to 2009, 91 incidents per year on average from 2010 to 2019; and a running average of 50 incidents per year from 2020 to 2023.

Over the past several years, communities have experienced extreme storms that compromise dams. Stormflows from these events can, and often do, exceed dam design specifications. Failures often occur when extreme storms coincide with aging dams that are in poor condition. Operations of California's Oroville Dam relied on a reservoir operation manual published in 1970 and the spillway failed during an unusually wet period[12]. The failure of Michigan's Edenville and Sanford dams in 2020 following extreme rainfall made national headlines[13]. There were dam failures throughout the country due to extreme weather events in 2024. Rapidan Dam in Minnesota was in poor condition and partially failed after days of intense rainfall that resulted in some of the highest flows on record[14]. North Carolina's Lake Lure Dam nearly failed when it overtopped during Hurricane Helene[15]. While the dam did not fail, it was a near miss. Forty regulated, mostly high-hazard, dams were impacted by Hurricane Helene. Dozens of additional non-jurisdictional dams and those dams regulated by the federal government were also damaged. Vermont experienced multiple historic flooding events throughout July and August 2024 when at least five dams failed and 50 dams sustained enough damage to require repair. These events point to the imminent need to remove outdated or unsafe barriers to bolster climate resilience and protect human life.

9 Data for dam hazard and dam condition are available from the National Inventory of Dams. Dams in less than satisfactory condition include those rated as fair, poor, unsatisfactory, unavailable, and not rated.

10 More information about increasing dam hazard is available from the Association of State Dam Safety Officials.

11 Data about dam failures are available from the Association of State Dam Safety Officials.

12 See the Oroville Dam Spillway Incident Independent Forensic Team Report for details.

13 See Investigation of failures of Edenville and Sanford Dams Independent Forensic Team Report.

14 Dams in distress: Partial failure in Minnesota offers a nationwide warning. NBC News.

15 North Carolina Lake Lure Dam failure update: People must leave immediately. Newsweek.

Addressing lost dam utility while increasing community services

Persistent multi-year droughts reduce inflow to reservoirs, diminishing hydropower and water supply benefits of dams. For example, during droughts hydropower generation has fallen below expectations in key power-producing regions such as the Columbia, Colorado, Sacramento, and Rio Grande Basins[16]. And not all hydropower facilities produce clean electricity; some reservoirs emit greenhouse gases, particularly methane, which is a potent contributor to increasing global temperatures. This has led some entities to advocate for replacing hydropower with other renewable energy sources, such as solar and wind, which combat climate change, do not contribute to greenhouse gas emissions, and support healthy rivers[17]. Small dams also lose utility because of sediment accumulation.

The reduced utility of climate change-impacted dams may also create finance problems for dam owners and operators who are generally funded through water sales and hydropower generation. Reduced future revenue from water contracts and hydropower generation may prevent owners from conducting timely upgrades or maintenance for aging dams, which present the largest risk of failure. Most dams are built with a design life of about 50 years, and after that time require significant operation and maintenance investments to prevent failure. By removing obsolete dams and transitioning to underground storage for water supply, and alternative energy sources like solar and wind, we can help communities prepare for future drought impacts. This energy transition also reduces economic impacts to communities who fund dam operation and maintenance through their utility rates.

Restoring traditional customs and food sovereignty for Tribes

Reconnecting rivers by removing barriers is also a means of climate resilience for Tribes by preserving cultural practices and restoring cultural fish harvests. Dams were frequently built in and flooded areas that are culturally important for Tribes, including Tribal gathering sites, celebration sites, and ancestral community sites. Dams have severely impaired populations of native fish populations that Tribes have depended on for millennia. Restoring fish passage and access to cold water refugia is a necessary act of preserving and respecting Tribal traditional customs.

16 For example, see this In Brief Analysis by the US Energy Information Administration.

17 Haemmerli et al. 2024 review diverse views on the role of hydropower in the US energy future.

Reconnecting rivers for resilient landscapes and fisheries

Removing obsolete dams to reconnect rivers can have an outsized benefit to landscapes, far beyond ecological improvement at the dam site itself. Reconnecting rivers provides access to diverse habitats necessary for stable fishery populations, including cold water refugia that will help aquatic species survive during extreme and prolonged drought. In addition, river reconnection allows for the transport of sediment downstream where the sediment may offset the effects of sea level rise on coastal communities. In other instances, connecting the physical and ecological function of rivers is described as a catch-all nature-based solution to adapt to climate change.

As climate conditions change, removing obsolete dams to reestablish fish passage is often crucial for fish health, population growth, and species survival—particularly for migratory fish species, like salmon, trout, and herring. River fragmentation from dams and instream structures has been a primary threat to migratory fishes, endangering species, isolating populations, and reducing genetic and life history diversity essential to maintaining stable fish populations. The changing climate adds an additional stressor to these already diminished populations. Further climate change-related harms are expected such as increasing water temperatures that reduce appropriate fish habitat, increasing presence of harmful algae blooms and toxins that impair water quality, and decreasing water availability during already dry periods that reduce summer and fall streamflow. Removing stream barriers to provide access to upstream river reaches and headwaters is broadly valued to improve the resilience of fish species and populations to these anticipated changes.

Providing access to cooler upstream water temperatures

Fish, especially native species, are sensitive to water temperatures. As air temperatures warm, stream temperatures also warm, limiting availability of and access to cold-water ecosystems. Many dams and stream barriers hold back water in reservoirs that becomes increasingly warm and prone to toxic algal growth, which then also increases water temperatures and toxicity downstream when reservoir water is released. One solution is to remove stream barriers to provide access to cooler headwaters and upstream reaches. This approach provides suitable water temperatures for fish and other biota as air temperatures warm, while avoiding the effort and expense of ongoing management by people.

Providing access to cooler headwaters increases the ability of fish to respond to climate events, such as droughts, heat waves, warm seasons, and other climate extremes. During such events, fish can travel to less impacted areas of a river when dams do not block access. Findings suggest that, under the right conditions, removing dams and barriers can offer substantial benefits as a nature-based solution for climate resilience to warming stream temperatures.

METRICS FOR CLIMATE RESILIENCE

Measuring climate resilience is challenging because resilience goals differ among dam removal projects. Some dam owners remove dams that are no longer economically viable; others remove dams for fisheries restoration or to increase the safety of downstream communities at risk of flooding. Also, each river system is unique, so there is no one-size-fits-all approach to improving and measuring climate resilience. Best practices include: (1) describing the anticipated climate change-related threat; (2) identifying the desired climate resilience benefits; (3) identifying solutions to address anticipated issues; and (4) developing metrics to assess those objectives. (Table 1). Measuring climate resilience can be as straightforward as identifying reconnected river miles or area of floodplain that can recharge groundwater supply following dam removal, but may become more specific, depending on a community's climate resilience goals.

CLIMATE IMPACT (Resilience to what?)	**CLIMATE RESILIENCE BENEFIT** (Resilience for what?)	**NATURE-BASED SOLUTION**	**METRICS** (Units)
Warming stream temperatures	Access to cooler stream reaches for salmon and trout	Reconnect stream/ river reaches	• Days exceeding temperatures appropriate for cold water fisheries (count) • Maximum of the 7-day maximum temperature (^{0}F) • Connected river length (miles)
Drought and climate variability	Diversity of habitats and species	Reconnect stream/ river reaches	• Number of species (count) • Abundance of species (count) • Prevalence of habitat types (%) • Connected river length (miles)
Extreme precipitation and flooding	Human health and safety	Provide space for flood flows and dampen floods	• Return period of historical 100-year flood (yrs) • Change in average annual streamflow (cubic feet per second) • Probable maximum flood (cubic feet per second)

TABLE 1. *Example climate impacts, climate resilience benefits, nature-based solutions, and metrics to evaluate climate resilience from removing dams and barriers*

REASONS THAT DAMS PROVIDE CLIMATE RESILIENCE

While removing dams can often enhance climate resilience, it is not practical everywhere. Figure 3 illustrates the variety of climate resilience benefits that some dams provide. For dams that provide cost-effective services and are well-maintained, re-operating existing dams is a common climate adaptation strategy. This might include updating reservoir storage and release rules to better accommodate winter storm runoff or using reservoir releases to provide suitable streamflows and temperatures for ecosystems[18]. In places where removing dams is not practical, new storage and coordinated management of surface and groundwater storage are promising strategies to adapt water supply and flood risk reduction to a warmer climate.

18 Ho et al. 2017 offer a perspective on the future role of dams in the US.

CLIMATE RESILIENCE BENEFIT STUDIES

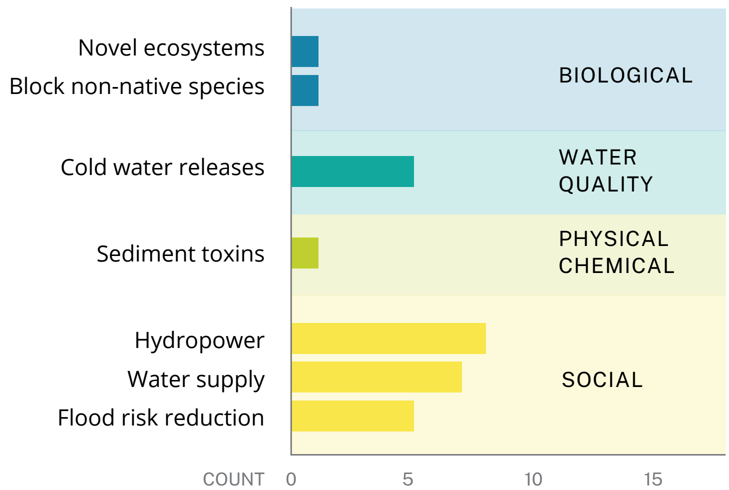

FIGURE 3. *Number of studies that identify climate resilience benefits of dams and/or barriers. This list provides a sample of benefits. It is not a complete review.*

CONCLUSIONS
AND DIRECTIONS FOR THE FUTURE

Recent research suggests that removing underperforming, dangerous, and obsolete dams and barriers improves resilience to flooding, drought, hydrologic variability, increasing temperatures, sea level rise, and changing river habitat conditions. Key benefits include reconnecting rivers, providing fish and wildlife access to cooler water in headwater reaches, and eliminating the safety risks posed by aging, outdated dams. These results show that resilience can—and should—factor into dam removal decision-making.

Significant knowledge and implementation gaps remain. They include defining resilience goals and objectives for dam removals and identifying metrics to effectively measure resilience. Results can be affected by droughts, fires, extreme precipitation, or other climate change-related threats that cloud the effects of dam removal. Studies to predict the effects of removing dams and barriers also have shortcomings. For example, about a third of models developed to predict likely effects of removing dams represent historical conditions instead of expected future conditions.

Finally, human and ecological systems are complex, and sometimes include unforeseen responses. For example, more research is needed to determine when reservoir operation adjustments can adequately address downstream cool-water temperature demands versus when barrier removal is the most efficient and effective way to provide fish direct access to cooler and more resilient upstream habitat. Future research should also evaluate how to manage ecosystems as a result of changing climate, the extent to which reduced populations of fish and wildlife will recover with altered future conditions, and how the spread of harmful algae blooms and fish parasites will impact species. Filling these gaps will build a clearer picture of climate resilience benefits and limitations of dam and barrier removal.

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