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EDITED AND REVIEWED BY
Fernanda Michalski,
Universidade Federal do Amapá, Brazil

*CORRESPONDENCE
Rebecca McCaffery
rmccaffery@usgs.gov

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Editorial: Large-scale dam removal and ecosystem restoration

Rebecca McCaffery[1]*, Jeffrey J. Duda[2], Laura Soissons[3] and Jean-Marc Roussel[3]

[1]U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Corvallis, OR, United States,
[2]U.S. Geological Survey, Western Fisheries Research Center, Seattle, WA, United States,
[3]DECOD (Ecosystem Dynamics and Sustainability), INRAE, Institut Agro, IFREMER, Rennes, France

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Editorial on the Research Topic
Large-scale dam removal and ecosystem restoration

1 Introduction

Rivers underpin vital ecosystems that support aquatic and terrestrial biodiversity and many ecosystem services, including food, water, culture, and recreation (Dudgeon et al. 2006). After centuries of building dams on rivers across the world, river restoration via dam removal is receiving increased public attention, financial investment, and scientific study because of various issues of regarding dam infrastructure, such as obsolescence, sedimentation, and ecosystem degradation (Duda and Bellmore, 2022; East and Grant, 2023). Most dam removal projects to date have focused on smaller structures, but larger structures > 10 m tall have also started to be removed in increasing numbers. Recent estimates suggest that only a small fraction of all dam removals have been scientifically studied, with most focused on small dams and short time scales (Bellmore et al., 2016). Understanding the outcomes of large dam removal, where case studies are much more limited, depends on sustained research and monitoring efforts aimed at understanding restoration processes over large spatial and temporal scales (Figure 1). The ecological and socio-ecological study of large dam removal represents a new frontier in dam removal research: projects are larger, more recent, and provide an opportunity to understand the complex ecological changes and impacts to humans that occur with these transformative restoration projects.

This Research Topic contains a diverse array of large dam removal research studies to synthesize the issues, outcomes, tools, and study designs used to document river and ecosystem responses across physical, biological, and ecological domains. Papers address ecosystem ecology and water quality, diadromous and migratory fish populations, terrestrial ecology, and human systems, exploring dam removal effects and impacts in the first ten years since large dam removal in unique river systems found in North America

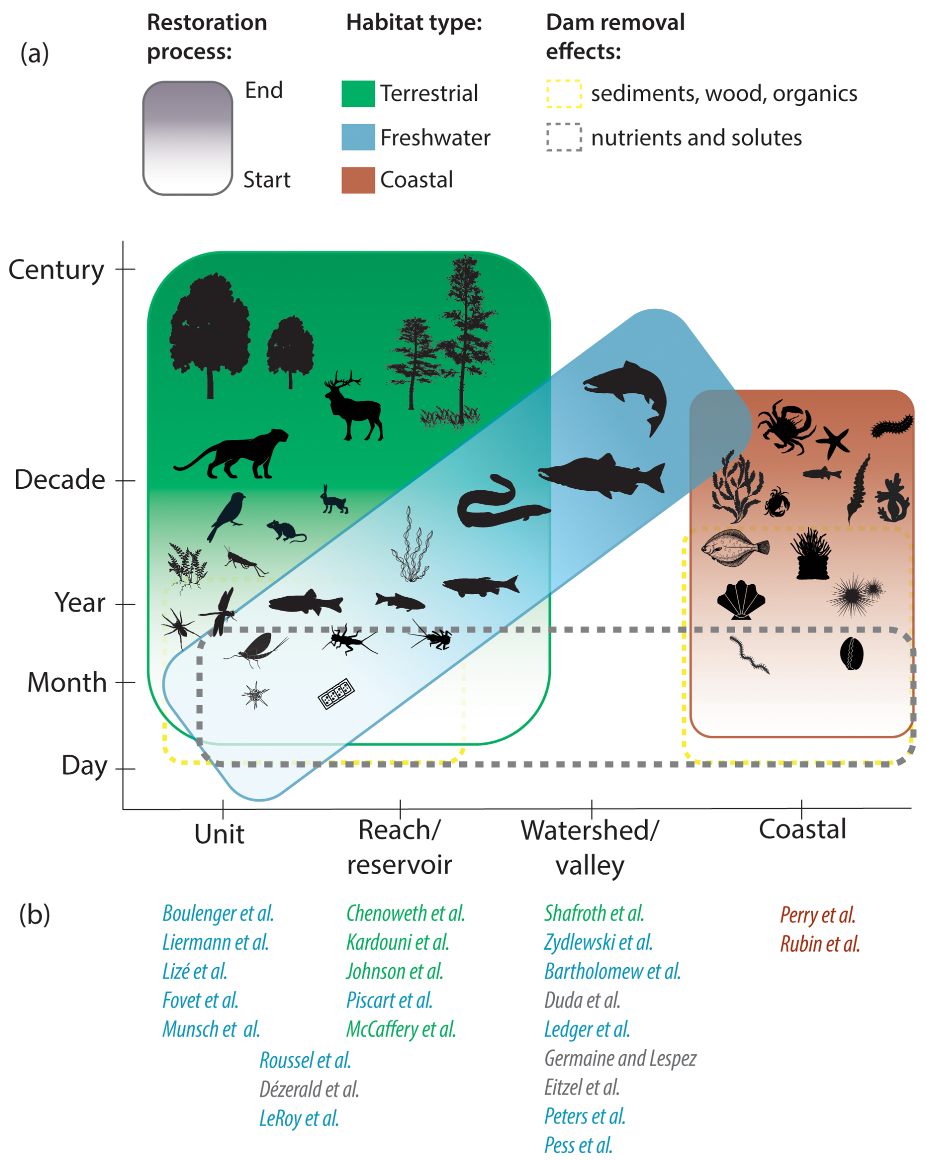

FIGURE 1
(A) Large dam removal influences multiple ecosystems over large spatial and temporal scales. Restoration processes are expected to occur from a span of days to decades and extend from microhabitats in the terrestrial and aquatic environments to trans-ecosystem influences. Processes include abiotic changes in sediment, wood, and water quality as well as diverse biotic and successional changes in freshwater aquatic, terrestrial, and coastal/marine ecosystems. **(B)** The papers in this Research Topic span riverine, terrestrial, and coastal ecosystems, examining dam removal issues and impacts in the first decade following large dam removal. The font colors highlight whether each paper covers freshwater (blue), terrestrial (green), coastal (brown), or multiple (grey) ecosystems.

and Europe. This Research Topic informs ongoing, long-term ecological restoration and monitoring projects related to dam removal as well as to upcoming large dam removal projects. Most of the papers focus on two large dam removal systems. The first is the Elwha River in Washington State, USA, where researchers have had 10 years or more to study post-dam removal outcomes using several scientific lenses. The second is the Sélune River in Normandy, France, where two dams were removed in 2019 and 2022. Finally, the Research Topic includes a review of dam-related challenges to fish and how removal of two dams mitigated some passage problems for the Penobscot River, Maine, USA; a modeling tool developed and tested on the Touques River in Normandy, France, to assess diadromous fish runs in restoration projects; and an exploration of how current removal of four dams on the Klamath River in California and Oregon, USA, could impact fish and fish disease dynamics.

2 Ecosystem ecology and water quality

The role of connections between ecosystems has long been acknowledged in ecological science, questioning the simplistic vision of compartmentalization of ecological processes (Summerhayes and Elton, 1923; Odum et al., 1979). The emergence of the meta-ecosystem framework (Loreau et al., 2003; Angeler et al., 2023), which considers flows of energy across ecosystem boundaries, highlights how adjacent ecosystems depend on each other across spatial and temporal scales. Conversely, alterations of ecological continua and transfers between ecosystems can affect their sustainability and resilience (e.g., Ward and Stanford, 1995; Baxter et al., 2004). In this first section, six articles address the multiple effects of large dams and their removal on the terrestrial–freshwater–marine continuum, highlighting perceptible impacts on water quality, plant and animal communities, and ecosystem functions. Roussel et al. report that the retention of sediment and nutrients in reservoirs can modulate the balance between detritus-based and algal-based food chains, altering the patterns of carbon flow in aquatic food webs along the river continuum. Fovet et al. demonstrate that fluxes of nutrients and sediments restore quickly after dam removal and become available again to aquatic life downstream after decades of sequestration into reservoirs. LeRoy et al. focus on a functional aspect of riverine ecosystem response by studying the decomposition of terrestrial-derived leaf litter by aquatic fungal and macroinvertebrate communities and show how this ecosystem function varies along the upstream-downstream gradient after dam removal. Similarly, Piscart et al. observe a rapid reestablishment of benthic macroinvertebrates in river segments within the footprint of a former reservoir, but also point out that fine sediment and instability of benthic habitats can delay the restoration of the whole river metabolism. Looking beyond the river itself, Dézerald et al. document the fast and simultaneous recovery of aquatic invertebrate, riparian invertebrate, and vegetation communities after reservoir dewatering, while demonstrating ongoing changes between communities as systems go through transient recovery phases. Finally, Rubin et al. illustrate the variable ecological responses among subtidal communities of kelp, benthic invertebrates, and fish following a massive sediment export after dam removal and the restoration of natural rates of terrestrial sediment transfer toward marine habitats.

3 Diadromous and migratory fish populations

There is keen interest in the response of fish populations to increased longitudinal connectivity from dam removal (Branco et al., 2014, Magilligan et al., 2016; Thieme et al., 2023). The bulk of the current dam-removal literature deals with documenting fish passage, estimating the amount of longitudinal habitat access restored, and changes to upstream fish assemblage structure. Most of these studies are of relatively short duration, a characteristic of most dam removal (Bellmore et al., 2016) and river restoration (Bernhardt et al., 2005) efforts. Several papers in the large dam removal Research Topic go beyond these structural-style studies and delve into topics that deal with fish functional responses to dam removal. Ledger et al. use genetic tools and a riverscape approach to examine the spatial structure of neutral genes and two genes associated with early migration timing in Steelhead and Chinook Salmon, finding limited genetic spatial structure in both populations (a result documented in pre-dam removal studies) and an increase in early return timing alleles in *Oncorhynchus mykiss* (i.e., Rainbow Trout and Steelhead) samples. Munsch et al. explore how restoring connectivity through dam removal goes beyond simply providing access to river kilometers of habitat upstream; it also can provide a portfolio of different habitats and environmental conditions within which life history diversity of fish populations can emerge and diversify. Such diversity has been shown to promote resistance to environmental disturbance and long-term resilience of populations (Schindler et al., 2010, Moore et al., 2014, Munsch et al., 2022). Pess et al. examine 10 years of during- and post-dam removal data focused on Steelhead and Chinook Salmon, two species listed under the U.S. Endangered Species Act. They show that dam removal, hatchery production, and harvest restrictions interacted and contributed to population response, including increasing population size, spatial extent, and life history diversity. In another long-term study from the east coast of the U.S. with a different assemblage of diadromous fish, Zydlewski et al. highlighted seven influences of dams on fish populations and how dam removal reversed some of these effects. Lizé et al. establish baseline levels of carbon stable isotopes in a diadromous fish community prior to dam removal, using the data to examine dietary niche partitioning and levels of interactions and overlap before the river is free flowing again. Bartholomew et al. discuss the potential for dam removal to change river conditions—especially with regards to temperature and flow regimes—and how this might affect the ecology and dynamics of parasites and their salmonid hosts.

Two papers in the Research Topic contain methodologies and modeling approaches that can be used in fish abundance estimation for adults (Boulenger et al.) and juveniles (Liermann et al.), techniques that can be employed for restoration projects, including dam removal. Boulenger et al. used independent, synchronous data from acoustic cameras to estimate detection probabilities and daily fish passage estimates. Liermann et al. created a model to relate water temperature, spawning location data, growth, and movement models to predict the emergence timing and size of outmigrating juvenile Chinook Salmon.

4 Terrestrial ecology

In contrast to fish restoration and ecosystem ecology, restoration of terrestrial plant and wildlife communities following dam removal has received relatively little attention (Bellmore et al., 2016; Wieferich et al., 2021). However, the sediment pulse generated by large dam removal and the exposure of dewatered reservoir beds creates new surfaces both in the former reservoirs and downstream of dam sites for diverse plant and animal species to establish and subsequently influence restoration trajectories (McCaffery et al., 2018). There is also interest in understanding the ecological impacts of active revegetation efforts (e.g., seeding and planting native plants and removing invasive species) and how those interact with natural plant establishment to inform future restoration efforts. Finally, patterns of terrestrial wildlife use and activity are closely linked to changes in vegetation, restoration of fish populations (Call, 2015; Tonra et al., 2015), and response of aquatic biodiversity in these systems.

This Research Topic contains several papers examining aspects of revegetation following dam removal—both natural and managed—as well as one paper examining wildlife responses. First, Shafroth et al. provide an overview of vegetation response throughout the Elwha River watershed, explaining the rapid changes that occurred due to the sediment pulse that moved through the watershed as the dams were removed and how those are expected to attenuate as sediment dynamics stabilize. Chenoweth et al. provide a complete review of natural plant establishment as well as active revegetation efforts on the dewatered reservoir beds, including initial predictions and actual patterns of revegetation. In Kardouni et al., authors focus specifically on the impacts of riverbank lupine (*Lupinus rivularis*) seeding efforts on ecosystem dynamics in the dewatered reservoirs in the Elwha River. Staying in the dewatered reservoir habitat, Johnson et al. describe how strategic placement of large wood as part of the restoration process can potentially enhance tree growth by mitigating moisture and nutrient limitations as well as protecting planted seedlings from ungulate browsing. Dézerald et al. describe the rapid establishment of new vegetation communities in the immediate years following dam removal, while highlighting the dynamic nature and rate of change present in these areas. Moving downstream to the coastal environment, Perry et al. describe vegetation establishment on new surfaces created by sediment mobilization during dam removal relative to existing coastal vegetation communities, and how those surfaces have changed as sediment dynamics stabilized in the 10 years since dam removal. Finally, turning to terrestrial wildlife, McCaffery et al. used camera traps to investigate mammalian wildlife use of dewatered reservoirs in the Elwha River ecosystem as restoration approaches the 10-year mark, demonstrating differences in species use by season and study reach.

5 The human connection: social science, political ecology, and economics

There are far fewer studies of social aspects of dam removal than those focused on physical and ecological outcomes (but see Sneddon et al., 2017; Leisher et al., 2022; Lutter et al., 2024), and most focus on local controversies (e.g., Jørgensen and Renöfält, 2013; Fox et al., 2016; Germaine and Lespez, 2017; Magilligan et al., 2017), management concerns (Tullos et al., 2016), or economic elements related to cost or property values (Loomis, 1996; Lewis et al., 2008). In this Research Topic, several case studies highlight the intersection of ecological, sociological, and natural resource management involved with dam removal and the recovery of a river and its valley. They also indicate that each component of the ecosystem can respond at a different pace, sometimes at large spatial scales, during the restoration period. The outcomes of large-scale dam removal projects inevitably affect the human communities living upstream and downstream of the dam to be removed, and they should be prepared and familiar with the details of the process as early as possible. Germaine and Lespez compare dam removal implementation details and social settings of the Elwha River (most of the watershed in a National Park) and the Sélune River (a rural European setting), stressing the importance of incorporating human relationships and attachment to local places as part of the dam removal context. Based on the Elwha River experience, Eitzel et al. give useful recommendations for successfully involving citizens in dam removal scientific studies, using a participatory science approach. Setting up large-scale dismantling programs also questions our capacity to cope with divergent management goals among partners and stakeholders, as pointed out by Peters et al. regarding the adaptive management of Endangered Species Act-listed salmonid populations on the Elwha River. Finally, on the economic level, Duda et al. describe a database of 668 dam removals in the USA with reported costs and cost drivers, creating a model of dam removal cost as a function of parameters such as the size of the dam, river, and project complexity based on the presence of cost items related to construction, mitigation, and post-removal outcomes.

6 Conclusion

At its simplest, the removal of a large dam from a river is about linear reconnection, restoring the unimpeded downstream flow of water, sediment, and nutrients while restoring the ability of aquatic organisms to move freely upstream, downstream, and out to the ocean as their life histories dictate. But the reality is much more complex, in ways we are only starting to fully appreciate. The research in this Research Topic and other recent synthesis efforts (Magilligan et al., 2016; Tonitto and Riha, 2016; Foley et al., 2017; Major et al., 2017; Bellmore et al., 2019) show that rivers and their denizens can respond quickly to large dam removal and the resulting restored longitudinal connectivity. Although scientists have a much better understanding of the initial and often large response to the act of dismantling a large dam from a river, the tail of the response distribution has been neglected (Figure 1). Recovery can start quickly for physical processes (e.g., flow, sediment, and temperature regimes) and some organisms with short lifespans like invertebrates, while riparian communities and fish populations can take longer to recover or document a signal from often noisy data. This Research Topic also highlights underappreciated restoration and responses of areas far from the location of large dam removal, such as coastal and subtidal ecosystems. This highlights the far-reaching, cross-boundary nature of restoration following dam removal and showcases broad linkages across ecosystems.

Despite our widespread advertising requesting submissions of large dam removal studies to be included in this Research Topic, only a small number were available to answer the call. The number of case studies, their geographic representation, and the temporal scale of impacts to river systems remains limited, highlighting the importance of continued research in the long term into this understudied area of river restoration. With such expansion, future synthesis efforts can draw from a larger pool of case studies, identifying unique features, generalities, and overarching lessons that can inform future practice and prioritization. Strategic implementation of comprehensive, long-term studies of key large dam removal efforts can be combined with efforts to document the location, focal species, dam characteristics, removal timeline, methods, costs, and associated drivers for all dam removal projects. Together such efforts could provide essential guidance to widespread efforts to restore river ecosystems and recover imperiled species.

Author contributions

RM: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. JD: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. LS: Conceptualization, Writing – original draft, Writing – review & editing. J-MR: Conceptualization, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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