Wiley Interdisciplinary Reviews: Water

WILEY

WIREs WATER

OVERVIEW OPEN ACCESS

Beaver Versus Human: The Big Differences in Small Dams

Ellen Wohl[1] | Shreeram Inamdar[2]

[1]Department of Geosciences, Colorado State University, Fort Collins, Colorado, USA | [2]Department of Plant and Soil Sciences, University of Delaware, Newark, Delaware, USA

Correspondence: Ellen Wohl (ellen.wohl@colostate.edu)

Received: 16 May 2024 | **Revised:** 21 February 2025 | **Accepted:** 9 March 2025

Associate Editor: Thomas Hartmann | **Editor-in-Chief:** Jan Seibert

Funding: The authors received no specific funding for this work.

Keywords: carbon | check dams | mill dams | nutrients | sediment

ABSTRACT

As beavers (*Castor* spp.) are reintroduced to streams in the northern hemisphere and nature-based and process-based river restoration emphasizes human-built analogues for beaver dams, it is reasonable to ask how beaver dams and ponds compare to different types of small dams constructed by humans for diverse purposes. We use published research as a basis for comparing the effects of beaver dams and four types of human dams—beaver dam analogues, earthen embankments perpendicular to flow that are used to create stock ponds, check dams, and mill dams. We compare these dams with respect to water balance and three-dimensional hydrologic connectivity, sediment, particulate organic matter and carbon, nutrients, habitat, and biota. These assessments inform us in ranking small dams from generally most beneficial with respect to providing ecosystem services (beaver meadows with multiple dams) to least beneficial (mill dams), recognizing that beaver meadows may not be beneficial at some sites for infrastructure and human property within the river corridor, and mill dams may be beneficial at some sites where they impede upstream migration by invasive species or provide lentic habitat in the river corridor. This comparison among dam types highlights the need for research on the cumulative effects of multiple small dams along a river corridor and across a river catchment, as well as identifying gaps in our understanding of the effects of specific types of dams, including the effects of stock ponds and check dams on carbon and nutrient dynamics.

1 | Introduction

The reintroduction of beavers (*Castor* spp.) and the mimicry of beaver dams by human-built structures have become increasingly popular and more commonly used in the management of smaller rivers in the northern hemisphere during the past two decades (e.g., MacDonald et al. 1995; Pollock et al. 2014; Johnson et al. 2020). This gives rise to the question of how the effects of beaver dams on ecosystem services compare to the effects created by other relatively small, human-built dams, such as mill dams, check dams, and stock ponds, which can be numerous and widespread in smaller rivers. Our primary objective in this paper is to systematically compare and contrast these effects with respect to multiple processes relevant to ecosystem services, including water, sediment, and nutrient dynamics, habitat, and biodiversity.

We consider beaver dams versus human dams. We define beaver dams as those built by *Castor canadensis* in North America and *Castor fiber* in Eurasia (Naiman et al. 1988; Larsen et al. 2021). Under the category of small human dams, we include four types: (i) human-built structures designed to mimic the height and width of beaver dams and known as beaver dam analogues (Pollock et al. 2014), post-assisted log structures (Jordan and Fairfax 2022), and other names; (ii) mill dams built across channels and valley floors to raise the water levels to run watermills (Walter and Merritts 2008; Buchty-Lemke and Lehmkuhl 2018;

Brykała and Podgórski 2020); (iii) check dams used for water and particularly sediment storage in smaller channels (Piton et al. 2017; Frankl et al. 2021; Lucas-Borja et al. 2021); and (iv) embankment or stock ponds, which are created by building sediment berms across small channels and valley floors for the purpose of storing water for agricultural use or limiting channel incision, typically in semiarid or arid regions (e.g., SCS 1982; Canals et al. 2011). We do not include fish or aquaculture ponds in the category of stock ponds. We include these four types of human-built dams because they are most closely analogous with respect to beaver dams in their limited height (< 5 m) and length, as well as their location on relatively small rivers and streams. We also include only structures explicitly identified as dams. We do not include other water-retention features such as natural or human-built depressions (wetlands, ponds, lakes) that are not dammed at the downstream end, nor do we include constructed wetlands with a dam.

We do not consider large or very large (commonly defined as > 15 m tall) human-built dams designed for purposes such as flood control, hydroelectric power generation, and water supply. In a meta-analysis of studies of beaver dams and human-built dams, Ecke et al. (2017) compared the number of studies describing dam-related alterations in hydrology, sediment, biogeochemistry, habitat, and biodiversity. They concluded that both types of dams similarly influence biodiversity but have contrasting effects on nutrient retention (e.g., young beaver ponds may be a source of phosphorus and mercury that change with age of the beaver pond). However, many of the dams represented in their analysis were larger than those considered here. As Ecke et al. (2017) noted, studies on small artificial impoundments are rare, although the median impoundment size in their review was 1367 ha, and they excluded the largest systems. They did not discuss the possible effects of the different numbers and locations within river networks of beaver dams versus human dams.

It is important to note that the four types of human-built dams considered here are chosen to serve a particular purpose associated with economic value and, in the case of beaver dam analogues and sometimes stock ponds, ecosystem services. In other words, locational choices by humans and beavers may not be driven primarily by the ecosystem benefits and costs that we consider here. However, any dam has ecosystem benefits and costs. Comparing these between different types of dams helps to inform the question that we have been asked by water resources practitioners and by citizens as to whether human-built small dams dispersed throughout the landscape create ecosystem effects similar to those of beaver dams.

We first review relevant ecological characteristics of *Castor* spp. and their dams. We then review basic characteristics of the four types of small human dams to which we compare beaver dams. Finally, we compare and contrast the effects of individual beaver and human dams and the potential cumulative effects of these different types of dams at the catchment scale.

2 | Beavers and Their Works

Beavers are large, semi-aquatic rodents that build lodges of sediment and wood surrounded by a pre-existing lake or pond or by a pond created by the backwater of a beaver dam on a flowing stream. The animals can also dig dens into the banks of rivers too large to dam. Beavers prefer to have the den entrance underwater to deter predators (Baker and Hill 2003). This partly governs the characteristics of their dams with respect to height and placement. An important consideration is that a beaver colony, which consists of a mated pair and their offspring (totalling 2–12 animals) (Baker and Hill 2003), commonly builds multiple dams in the river corridor. These dams can cross the main channel, secondary channels, tributaries, and seeps and springs along the valley margin. Many of the dams are not perpendicular to the main flow direction (Table 1). Ronnquist and Westbrook (2021) distinguished six types of beaver dams based on how water flowed through or over the dam. They found that physical differences in dam structure alter the dynamics and variance of pond storage. We lump all beaver dams together in this paper based on our understanding that the differences between beaver and human-built small dams are likely to be greater than the differences among beaver dams.

In a valley floor wide enough to host a floodplain, beavers can create a beaver meadow (Ives 1942; Polvi and Wohl 2012). Multiple beaver dams and ponds of varying ages within the beaver meadow create a three-dimensional mosaic composed of landscape patches of varying topography, substrate grain size, soil moisture, and vegetation communities (Figure 1). As individual dam-pond pairs are abandoned by the beavers, the ponds gradually fill with mineral sediment and organic detritus. The dams can be partially breached but remain as discontinuous berms (1–1.5 m tall) that become stabilized by vegetation such as multi-stemmed willows (*Salix* spp.) (Wohl et al. 2022). The irregularly varying floodplain topography of a beaver meadow can be compared to a waffle iron or an egg carton. Individual beaver meadows may be maintained by the beavers for hundreds to thousands of years (Kramer et al. 2012; Polvi and Wohl 2012).

Beavers are recognized as both keystone species and ecosystem engineers (Wright et al. 2002; Brazier et al. 2021) because of their substantial effects on resource availability, including habitat (Wright et al. 2002; Hood and Larson 2014) and nutrients (Lazar et al. 2015; Puttock et al. 2017). Beavers also commonly increase biomass and biodiversity for a diverse array

TABLE 1 | Basic characteristics of beaver dams versus human dams.

Beaver dams	Human dams
Permeable	Impermeable (except for beaver dam analogues)
Transient/dynamic	Persistent/static
Variable orientation	Perpendicular to flow
Potential alternative surface flow paths	Typically, no alternative flow paths
↑↑ River corridor patchiness	↑ River corridor patchiness
May limit longitudinal passage of aquatic organisms	Likely to limit longitudinal passage of aquatic organisms (except for beaver dam analogues)

FIGURE 1 | Details of beaver meadows. (A) The central photo shows an overview of a beaver meadow along North St. Vrain Creek (NSV), Colorado, USA (flow from right to left). Inset photos clockwise from the upper left show (B) an active (recently built) beaver dam, Fall River, Colorado; (C) multiple channels converging in the NSV beaver meadow (flow is toward the viewer); (D) a beaver path that is gradually becoming a small secondary channel, NSV beaver meadow; (E) return flow from the inundated floodplain spilling over the banks into the active channel at base flow downstream from the beaver dam, Fall River; and (F) a relict, off-channel beaver dam in the NSV beaver meadow, with the former dam, now a vegetated berm, at right.

of organisms inhabiting and visiting the river corridor (e.g., Smith and Mather 2013; Hossack et al. 2015; Stringer and Gaywood 2016). Recognition of the importance of beavers has existed for centuries among indigenous peoples in North America and Eurasia (Coles 2000) and western naturalists have written of the environmental effects of beavers for more than a century (e.g., Morgan 1868; Mills 1913). More recent scholarship has systematically demonstrated how ecosystem modifications by beavers, mainly via herbivory and the construction of dams and canals, influence each of the processes and variables discussed in this paper (Grudzinski et al. 2020, 2022; Brazier et al. 2021; Larsen et al. 2021; Wohl 2021).

3 | Human Dams

People build dams for diverse reasons, including water supply for consumptive use, flood control, hydropower generation, milling and grinding grain, erosion control, and maintenance of minimum depth for navigation (Milliman 1993). More than 30,000 large dams (> 15 m tall) and 300 major dams (> 150 m tall) exist on the world's rivers (Zhang et al. 2018), but a much greater number of relatively small human-built dams also exist worldwide. Large dams receive much attention for their fragmenting and homogenizing effects on rivers (e.g., Poff et al. 2007; Grill et al. 2015; Spinti et al. 2023). Small dams can also longitudinally fragment rivers and alter hydrologic, sediment, and nutrient connectivity, as well as the distribution and abundance of habitat and biota (e.g., Chin et al. 2008; Liu et al. 2014; Fenci et al. 2015). We consider four types of smaller dams built to (i) mimic or replace beaver dams, (ii) power water mills, (iii) store water and sediment and stabilize channels (check dams), and (iv) create water sources for agriculture (stock ponds) (Figure 2).

The use of human-built beaver dam analogues (Pollock et al. 2012; Lautz et al. 2019) largely dates to the early 21st century and represents a response to the historic loss of beaver populations and beaver dams throughout the northern hemisphere (Pollock et al. 2014). Beaver dam analogues are typically constructed on small, intermittent to perennial streams. These structures are now being installed across the contiguous United States, in the United Kingdom, and in some countries of western Europe (Brazier et al. 2021; Wolf and Hammill 2023).

Mill dams existed on perennial channels and were abundant and widespread across Europe and North America prior to the 20th century (Walter and Merritts 2008; Barraud 2017; Buchty-Lemke and Lehmkuhl 2018; Brykała and Podgórski 2020). These dams are no longer used to run water mills, and many of the dams have breached through lack of maintenance or have been deliberately removed (e.g., Kanehl et al. 1997; Chaplin et al. 2005). Others remain in place, although we are not aware of any systematic inventory of existing mill dams in a particular region or across the world.

FIGURE 2 | Examples of types of human dams discussed here. (A) A mill dam in Pennsylvania, USA. (B) A river network with multiple earthen embankments in semiarid southern Wyoming, USA. (C) A close-up of one of these embankments. (D) Check dams in the Alptal region of Switzerland. (E) A beaver dam analogue in South Park, Colorado, USA.

Check dams of various materials have also been built for centuries, primarily in relatively steep channels to control erosion (Lucas-Borja et al. 2021). Check dams are especially common in drylands and in steep terrain. They may be constructed of relatively durable materials such as quarried rock or concrete, or of materials as transient as hay bales or piles of woody brush (Huzita et al. 2020; Pourghasemi et al. 2020).

Water-harvesting techniques in drylands (Rango and Havstad 2011) have existed for centuries. These techniques include the construction of earthen berms across perennial or ephemeral water courses to create stock ponds or water supplies for livestock. These structures are common in semiarid to arid environments such as those in interior western North America (Nichols et al. 2018), Africa (Wilson 2007), and Australia (Markwell and Fellows 2008).

Human-built small dams are built to pond water upstream via an impermeable or low-permeability barrier to downstream flow (except beaver dam analogues, which are typically permeable); typically oriented perpendicular to the main flow direction in a valley (Table 1); and designed to be persistent over timespans of a few years to several decades, although check dams in particular can fail within a few years in rapidly incising channels (Lucas-Borja et al. 2018). Beyond these commonalities, the details of human-built small dams can vary widely as a function of dam height, dam purpose, and valley geometry, as these influence the width, depth, and longitudinal extent of the flooded area, as well as seasonal to interannual fluctuations in water storage upstream from the dam (Merritts et al. 2011; Szatten et al. 2023).

4 | Dam and Pond Characteristics

4.1 | Beaver Dams

Constraining the range of size distributions for dams and ponds in any of the four categories being considered here is difficult because of the diversity of valley-floor and associated dam geometry. Beavers generally prefer wide valley floors with <6% stream gradient, intermittent to perennial flow, and suitable and sufficient riparian and wetland vegetation (Baker and Hill 2003). Beavers build dams at sites where peak flows are less likely to destroy the structure (Macfarlane et al. 2017); otherwise, they can dig streambank dens along large rivers or build lodges in existing waterbodies such as lakes. We have observed beaver dams on hillside seeps, however, and immediately upstream from waterfalls and on relatively narrow valley floors. The typical size range for dams is ~5–70 m long, 1–2 m wide, and 1–2 m tall, and reported dam densities along streams range from 2 to 18 dams/km (Butler and Malanson 1995). The largest reported dam is 775 m long in a remote area of Canada's Wood Buffalo National Park (https://www.pc.gc.ca/pn-np/nt/woodbuffalo/nature/beaver_gallery). The dam inundates approximately 70,000 m^2 of surface area and is estimated to be about 1 m deep. Individual dams may be maintained by the beaver colony for a single season or for several years, although there is also evidence of continuous occupation of at least some dams

and ponds for more than a century (Johnston 2015). Individual beaver ponds can persist for at least 150 years (Johnston 2015) and beaver meadows can be occupied for at least 5000 years (Kramer et al. 2012; Polvi and Wohl 2012).

The commonly cited estimate is 60–400 million *C. canadensis* in North America prior to European contact (Naiman et al. 1988), with a distribution from the Arctic tree line south to the US–Mexico border, except for parts of the arid Great Basin (Pollock et al. 2015). Contemporary *C. canadensis* populations are estimated in the range of 6–12 million individuals (Naiman et al. 1988). Based on the earliest written descriptions of areas in North America inhabited by *C. canadensis*, beavers were likely ubiquitous in suitable habitat along smaller streams and the floodplains of larger rivers. Contemporary *Castor fiber* population estimates in Eurasia are closer to 1.5 million individuals (Halley et al. 2021). We were unable to find historical population estimates for the Eurasian beaver, although the animals ranged across the forested regions of Eurasia (Rosell et al. 2005).

4.2 | Beaver Dam Analogues

The use of beaver dam analogues is a relatively recent development (e.g., Pollock et al. 2014; L. Lautz et al. 2019). No compilation of projects is available for the northern hemisphere, although at least 300 projects have been undertaken in North America as of January 2024 (LT-PBR explorer, https://bda-explorer.herokuapp.com/projects/map). The location, size, and spatial density of these dams are typically designed to mimic real beaver dams. Only a single dam is built at some sites, but more commonly multiple dams are built in sequence along the active channel. Most dams are designed to span the bankfull channel, rather than the entire floodplain. In some projects, it is considered permissible or even desirable for the channel to migrate laterally and flank the beaver dam analogue. Beaver dam analogues are built to be overtopped and have varying degrees of permeability. Typically, the structures mimic real beaver dams in having a series of upright wooden posts anchored in the streambed and banks, with smaller branches woven horizontally between these posts (e.g., fig. 1 in Lautz et al. 2019), but details of design can vary substantially between individual beaver dam analogues (Scamardo and Wohl 2020). Beaver dam analogues are likely to be built across the main channel in a valley and oriented perpendicular to flow, so that their geometry and placement are simpler and more consistent than those of beaver dams.

4.3 | Mill Dams

Although global compilations of abundance and distribution have been published for large dams, we were unable to find analogous information for mill dams, check dams, or embankment/stock ponds. Mill dams have been built for millennia (Wikander 2000; Angelakis et al. 2022; Szatten et al. 2023) but effective estimates of the density of dams along individual rivers or within a region can be challenging because of the burial or decay of ancient structures (e.g., Clay and Salisbury 1990; Merritts et al. 2013). Regional estimates for mill dams suggest locally very high densities on suitable streams (Bishop and Muñoz-Salinas 2013). Walter and Merritts (2008), for example, inferred an average density of 0.14–0.15 dams per km^2 for the commonwealth of Pennsylvania, USA, with some localities having 0.61 dams per km^2. The common surname Miller and equivalents in other languages also reflect the large number of mills once used in grinding grain, sawing lumber and rock, and processing paper, textiles, and metal products. Similar assessments for mill types and locations, many dating to periods earlier than those in North America, have also been reported from Europe (Brykała and Podgórski 2020). Not all mills relied on a dam across an entire channel: on larger rivers, water might be diverted into a millrace to turn a wheel and then returned to the channel. Mill dams appear to have been typically in the range of 2.5–3.7 m tall in Pennsylvania, with the potential to reduce flow velocity by 60% at least 1–3 km upstream (Walter and Merritts 2008).

4.4 | Check Dams

Check dams include a diverse array of structures composed of concrete, loose rocks, rocks in gabion baskets, wood, brush, and metal that are built across channels, primarily with the intent of storing sediment and controlling erosion but also sometimes for attenuating flash floods (Lucas-Borja et al. 2021). These are among the oldest types of dams (e.g., Albinia 2010; Luzzadder-Beach et al. 2012) and are widespread globally, especially in moderate to high-relief environments and in drylands (Lucas-Borja et al. 2021). Check dams are particularly abundant in Asia and Europe. Individual dams are typically 3–7 m tall and 1–5 m wide, although the thorough review by Lucas-Borja et al. (2021) documented check dams 15 m tall and 200 m wide. Although individual check dams exist, it is more common to have multiple check dams in sequence along a channel and across multiple channels in a river network. Reported densities include 6 check dams per km^2 (Bombino et al. 2007), 1 dam per 3.9 km of channel (Conesa-García et al. 2007), and 22 dams per km of channel (do Prado et al. 2024). A quick Google Earth-based reconnaissance of channels known to the authors to contain check dams indicates densities of up to 10.2 and 14.9 dams per km of channel at sites in Japan and 22 and 15.5 dams per km of channel at sites in the mountains of Italy.

4.5 | Stock Ponds

Stock ponds are primarily designed to collect and store water in water-limited areas. Water storage via collecting rainwater or surface runoff utilizes many different techniques and structures, some of which were developed thousands of years ago in the Middle East and the Americas, and some of which were placed outside of river networks (e.g., on hillslopes) (Lowdermilk 1960; Bruins et al. 1986; Nichols et al. 2018); here, we only consider those built on channels, including ephemeral channels. Stock ponds also very effectively store sediment and at least a subset in the United States is monitored by the US Department of Agriculture's Agricultural Research Service as a source of information on sediment yields from upstream catchments (Lane et al. 1997; Nichols 2006). Only local estimates of stock pond density seem to be available, but spatial density can approach two ponds per km^2 of contributing area (Culler 1961) or two ponds per km of channel. The capacity of stock ponds also varies enormously between ponds. One study in the Cheyenne River catchment of South Dakota and Wyoming, USA, inventoried ponds with capacities from 6660 to 440,350 m^3 each (Culler 1961).

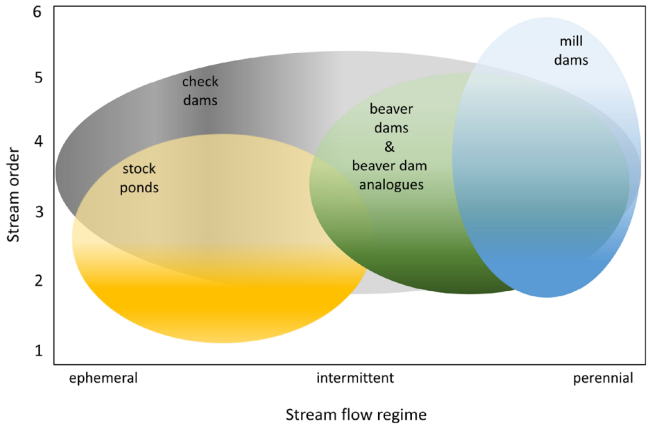

FIGURE 3 | Schematic illustration of the distribution of different dam types with respect to stream order (a surrogate for drainage area and bankfull channel width) and stream flow regime. Gradients within distribution ovals indicate that each type of dam is more common in the lower stream orders.

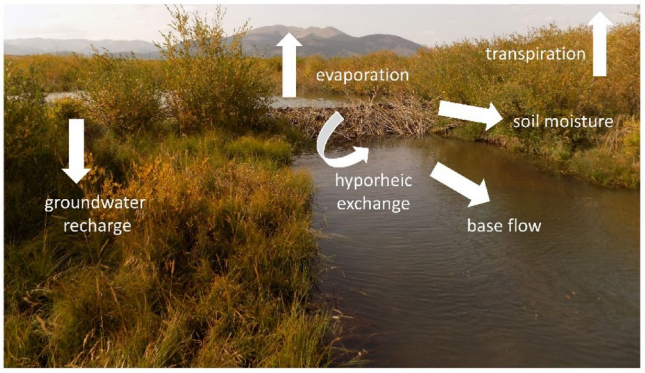

FIGURE 4 | Schematic illustration of the fluxes of moisture that can be enhanced by the presence of a dam and backwater. The background photo is from a beaver dam and pond in South Park, Colorado, USA.

Stock ponds are a subset of the small impoundments (< 2 m tall and mostly < 0.5 ha in ponded area) analyzed for the conterminous United States in Renwick et al. (2005). This analysis revealed 8–9 million ponds that capture an estimated 21% of the drainage area in the conterminous United States. These small impoundments, which are concentrated in agricultural areas, can be built by private landowners and by government agencies such as the Soil Conservation Service and have mostly been constructed since the early 20th century, with thousands of additional structures being built each year (Renwick et al. 2005). There are no published estimates of stock pond age, persistence, or duration of sediment retention, but the ponds presumably retain all trapped sediment until the earthen berm is breached.

4.6 | Comparison Among Types

All types of dams and ponds considered here include substantial overlap in their storage volume and in their maximum density (downstream spacing) on suitable streams (Table S1). Beaver dams and beaver dam analogues are likely to be less tall than mill dams, many types of check dams, or the earthen embankments of stock ponds. Mill dams, check dams, and earthen embankments are more likely to extend across the entire valley floor (Merritts et al. 2011) than individual beaver dams or beaver dam analogues. All are built on relatively small streams, with stock ponds most likely on first- to fourth-order channels, beaver dams and beaver dam analogues on second- to fifth-order streams, check dams on second- to fifth-order streams, and mill dams on second- to sixth-order streams (Figure 3). Beaver dams and beaver dam analogues are more common on intermittent and perennial streams, mill dams on perennial streams, and stock ponds on ephemeral and intermittent streams. Check dams are particularly common along ephemeral streams but are also built on intermittent and perennial streams.

5 | Dam Effects

As an obstruction to downstream fluxes within a river corridor, a dam influences the dynamics of water, solutes, and particulate material (sediment, organic matter). By altering the fluxes of material and the abundance and diversity of lotic, lentic, and riparian habitat, a dam also influences the abundance and diversity of biota. This section briefly reviews these effects, but the detailed effects of any particular dam depend strongly on the characteristics of the dam and the biogeomorphic setting in which the dam exists (Poff and Hart 2002).

5.1 | Water Balance and Three-Dimensional Hydrologic Connectivity

The effects of natural beaver dams and ponds on hydrologic processes have received more attention than those of beaver dam analogues, mill dams, check dams, or stock ponds. For beaver dams, the backwater upstream from a dam has lower velocity and greater surface area than flowing water upstream or downstream. This can attenuate flood peak flows (Norbury et al. 2018; Puttock et al. 2021). The dam backwater can enhance infiltration and groundwater recharge (Westbrook et al. 2006) and create a pressure gradient adjacent to the dam that enhances hyporheic exchange flows (Ledford et al. 2023). The dam backwater can also increase evaporation from the water surface and transpiration from floodplain vegetation (Burns and McDonnell 1998; Duesterhaus et al. 2008), especially because greater soil moisture adjacent to the dam backwater can support mesic and wetland vegetation with higher transpiration rates (Larsen et al. 2021) (Figure 4). The water balance associated with a dam backwater can vary substantially based on factors such as (i) volume, surface area, surface cover (e.g., aquatic macrophytes), and water temperature of the backwater; (ii) permeability of the underlying sediment; (iii) evaporative demand; and (iv) vegetation type, density, and moisture as these influence transpiration (Larsen et al. 2021). It is important to note, though, that comprehensive water balances at the reach-scale of a stream corridor have not yet been conducted or published, so it is not possible to quantitatively evaluate the effects of beaver dams, beaver dam analogues, and other small, human-built dams on water balance.

The hydrologic effects of beaver dams can vary significantly from those of human dams, however; limited study of old mill dams, for example, indicates that the dam and backwater raise

riparian groundwater levels upstream from the dam but do not otherwise create the same subsurface hydrologic exchanges as more pervious beaver dams (Sherman et al. 2022). Studies at some beaver dams indicate that stream water enters riparian sediment upstream from the dam and travels through the subsurface around the dam (e.g., Janzen and Westbrook 2011; Wang et al. 2018). Sherman et al. (2022) did not observe this at mill dams, perhaps because the impervious mill dams (constructed with sculpted rocks) spanned the entire stream valley and blocked downstream subsurface flow, and/or perhaps because the fine-grained mill pond sediments (Peck et al. 2023) had low hydraulic conductivity that precluded significant and sustained flow through the sediment. As Sherman et al. (2022) noted, valley-spanning mill dams are taller and more permanent than beaver dams and may create a more persistent influence on the amount and nature of riparian sedimentation. In the eastern United States, mill dams were also commonly built in relatively wet environments with perennial stream flow at a time when the removal of native upland vegetation for agriculture increased sediment yields to stream corridors from upland soils with substantial silt and clay content (e.g., Merritts et al. 2013). Investigations of mill-dammed rivers in western Europe indicate that mill-dam backwaters widened rivers, increased floodplain sedimentation, and increased the size of existing lakes or initiated secondary lakes, sometimes creating flooding that led to the abandonment of medieval rural settlements (Kaiser et al. 2018). Subsequent removal of those dams caused a net incision of the riverbed to a level below the original bed, reducing floodplain-channel hydrologic connectivity (Maaß and Schüttrumpf 2019).

The presence of a dam and backwater also alters three-dimensional (longitudinal, lateral, and vertical) hydrologic connectivity within a river corridor. As with other effects from dams, the details depend strongly on dam characteristics. Dams typically reduce longitudinal surface connectivity (Callow and Smettem 2009; Burchsted et al. 2010; Lucas-Borja et al. 2021). Dams may increase lateral connectivity by promoting overbank flows and channel lateral migration or avulsion if the dam backwater does not inundate the entire valley floor. Beaver dams and beaver dam analogues, unlike mill dams, check dams, and earthen embankments, typically increase overbank flows and channel lateral movement (John and Klein 2004; Westbrook et al. 2006). Beaver dams and beaver dam analogues can also increase vertical connectivity by promoting hyporheic exchange flows and groundwater recharge from the ponded water upstream from the dam (Lautz et al. 2006; Wegener et al. 2017; Munir and Westbrook 2021). Impermeable human-built dams that have accumulated fine sediment of low permeability in their backwater, in contrast, may have limited vertical and lateral (stream-riparian) hydrologic connectivity (e.g., Sherman et al. 2022). On the other hand, occasional lenses or layers of coarse sediments deposited upstream of the dams could allow for some hyporheic exchange between the stream and riparian sediments.

The effects of a dam can also vary with spatial scale. The earthen embankments used to create stock ponds are common in drylands, for example, where the pond can enhance recharge locally but limit downstream recharge by decreasing surface flow downstream, leading to deficits in downstream recharge zones (Heller 1999). Mill dams can also limit downstream surface flow and recharge, a scenario that Sherman et al. (2022) described as the dam shadow effect. In channels of arid and semiarid regions with flashy hydrology, sequences of check dams may promote surface water retention and groundwater recharge (Agoramoorthy et al. 2016; Djuma et al. 2017; Zhao and Wang 2021).

In summary, the limited comparisons in published literature suggest that relatively permeable beaver dams tend to enhance lateral and vertical hydrologic connectivity more than human-built small dams, with the exception of beaver dam analogues. Beaver dam analogues can enhance channel-floodplain and channel-hyporheic hydrologic connectivity, especially when these dams are built in sequence (Wade et al. 2020; Pearce et al. 2021). Existing literature on the effects of dams on hydrology typically focuses on a single aspect, such as the attenuation of peak flows, water storage, or hyporheic exchange. Our review of this literature reveals the need to develop more comprehensive water budgets for reaches of river corridor containing one or more dams, so that the cumulative and net effects of different types of dams can be quantitatively evaluated and compared.

5.2 | Sediment

Sediment is deposited and stored in a dam backwater as long as capacity is available. Consequently, as long as a beaver dam, beaver dam analogue, mill dam, check dam, or earthen embankment is intact, it traps some or all the sediment moving downstream and reduces longitudinal connectivity for this material. Renwick et al. (2005) estimated that the volume of sediment stored in small impoundments within the conterminous United States could be comparable to the volume stored behind larger dams that are included in the National Inventory of Dams. This study included all types of small impoundments, although the authors inferred that the impoundments included were "overwhelmingly of human origin" (Renwick et al. 2005, 102).

Beaver dams can be very effective at storing sediment (Butler and Malanson 1995; Wohl and Scott 2017). The volume of sediment stored behind individual beaver dams relates to factors such as dam height and pond size, as well as position within a sequence where multiple dams are present in series along a channel (De Visscher et al. 2014; Puttock et al. 2018; Dunn et al. 2024), but the relative permeability and transience of individual beaver dams are likely to result in backwater storage of smaller volumes of sediment with a coarser grain-size distribution than present in otherwise analogous human dams. A direct comparison of the sources of sediment stored behind beaver dams and beaver dam analogues in Alberta, Canada, indicated that terraces (56% of sediment retained), uplands (23%), and beaver dam canals (13%) dominated sediment sources for beaver dams, whereas eroding stream banks (89%) dominated sediment sources for beaver dam analogues (Westbrook and Cooper 2024). These differences may reflect the predominance of eroding banks in channels targeted for restoration using beaver dam analogues. There is no documentation of downstream sediment deficits that lead to enhanced channel erosion downstream from beaver dams (Bigler et al. 2001), even when the dam was removed or failed catastrophically (Butler and Malanson 2005). The limited

documentation of sediment storage at beaver dam analogues suggests much smaller volumes of stored sediment than those associated with beaver dams, probably in part because of the relatively recent construction of most beaver dam analogues examined thus far (e.g., Scamardo and Wohl 2020; Dunn et al. 2024).

Reduced longitudinal connectivity for sediment can create a sediment-deficit that increases bed coarsening and/or erosion of channel boundaries, especially downstream from a mill dam, check dam, or earthen embankment (Kondolf et al. 2002; Castillo et al. 2007; Bombino et al. 2008; Florsheim et al. 2013). Contemporary mill dams are historical relics, and there is little information on whether they caused downstream erosion when first built. Downstream erosion might have occurred based on documented channel responses downstream from more recently constructed dams (Collier et al. 1996), although some descriptions indicate that mill dams were so closely spaced that the distance between the base of a dam and the backwater from the next dam downstream was limited. It is also important in this context to note that mill dams were commonly constructed at the same time that native upland vegetation was being cleared for agriculture, which resulted in increased sediment yields to river corridors (Donovan et al. 2016), although the proportion of this sediment stored in mill ponds depended on the size of the dam and pond, the drainage area, and the downstream spacing of mill dams.

The great majority of contemporary studies on mill dams focus on breached dams and associated channel erosion within the ponded sediment and downstream increases in sediment and nutrient supplies. Sediment ponded behind mill dams can persist for centuries to millennia. The volume of sediment that accumulates behind a dam depends on factors such as sediment yield from the contributing area, trapping efficiency of the pond, size of the dam (width and height), and length of time the dam is present (e.g., Bishop et al. 2010; Johnson et al. 2023). The volume of sediment that persists after the dam is partly or completely eroded/decayed/removed depends on factors such as whether the pond is on or off a contemporary active channel, the erosional resistance of the ponded sediment versus the erosive force of processes such as streamflow and freeze–thaw weathering of the stream banks, the rate at which vegetation colonizes and stabilizes the ponded sediment and the erosional resistance added by the vegetation, and whether people choose to stabilize or remove contaminated sediment associated with the pond (Walter and Merritts 2008; Pizzuto and O'Neal 2009; Merritts et al. 2013; Fajer and Rzetala 2017; Podgórski and Szatten 2020). A commonly described scenario is accelerated erosion of ponded sediment through both incision and bank erosion after dam removal, along with downstream aggradation and bed fining (e.g., Lyons et al. 2015; Magilligan et al. 2016).

While the dam(s) is intact, the volume of sediment stored behind mill dams, check dams, and earthen embankments generally reflects dam height and backwater size, slope of the stream channel, sediment yield from upstream areas, position within a sequence where multiple dams are present in series along a channel, and trapping capacity and proportion of the backwater filled with sediment (Bombino et al. 2022). Check dams, in particular, can very effectively trap sediment in areas with naturally high sediment yields and rates of downstream transport because they are designed for this purpose. Decreased sediment load can lead to exacerbated erosion downstream (Lucas-Borja et al. 2021) and has led to replacement of closed check dams by "open" check dams that include large slits or slots designed to pass finer sediment and water downstream (e.g., Armanini et al. 1991; Schwindt et al. 2017) (Figure 5).

The net effect of beaver and human dams is to reduce longitudinal sediment connectivity within a river. The relative magnitude of this reduction can either cause downstream channel erosion while the dam is present and downstream aggradation caused by increased sediment supply after the dam is removed (e.g., mill dams, some stock ponds) or can result in no substantial change in downstream sediment dynamics (beaver dams). A dam that increases lateral hydrologic connectivity within the river corridor also increases lateral connectivity for particulate material, which can create valley-floor aggradation (Westbrook et al. 2011) and increase organic matter concentrations in floodplain sediments. Beaver dams are particularly effective in this respect, although check dams can also create channel and valley-floor aggradation (e.g., Bombino et al. 2014).

Galia et al. (2021) described an exception to the general trends above. Multiple check dams built along a small, steep channel in the Czech Republic that was also straightened between stabilized banks have filled with sediment since construction. Longitudinal coarse sediment connectivity was greater in this portion of the channel than in neighboring channels with natural pool-riffle bedform sequences that created hydraulic roughness.

In summary, dams typically store sediment and interrupt longitudinal sediment connectivity. Although investigators typically assess the interruption of longitudinal sediment connectivity qualitatively (i.e., based on downstream channel erosion), observations from diverse studies suggest that beaver dams and beaver dam analogues are least likely to create downstream channel erosion, even though they can effectively store sediment (Figure 6). Beaver dams, beaver dam analogues, and check dams are documented to have a greater potential to increase valley-floor (floodplain) aggradation than other types of small, human-built dams.

5.3 | Organic Particulate Material and Carbon

The lower velocity of a dam backwater results in the deposition of particulate material, including mineral sediment, organic matter, and materials adsorbed to sediment and organic matter, such as phosphorus and/or heavy metals. The trapping efficiency of the backwater depends on: (i) how the particulate material is traveling—material moving in contact with the streambed is more likely to be trapped than material moving in suspension; (ii) the degree to which the dam reduces flow velocity; (iii) the capacity to inflow ratio (Brune 1953); and (iv) the water residence time (Churchill 1948; Lewis et al. 2013). These generalizations apply to all types of small dams.

Particulate organic matter can accumulate and remain intact during burial or can decompose within the backwater (e.g., Mbaka and Mwaniki 2017). Backwaters can also

FIGURE 5 | Examples of different types of check dams. Upper left, open check dam in Italy; lower left, open check dam (although filled with sediment) in Austria. Upper and lower right, low (~1 m tall) and high (~6 m tall) closed check dams, respectively, in Japan. Lower center, a sequence of closed check dams in Austria.

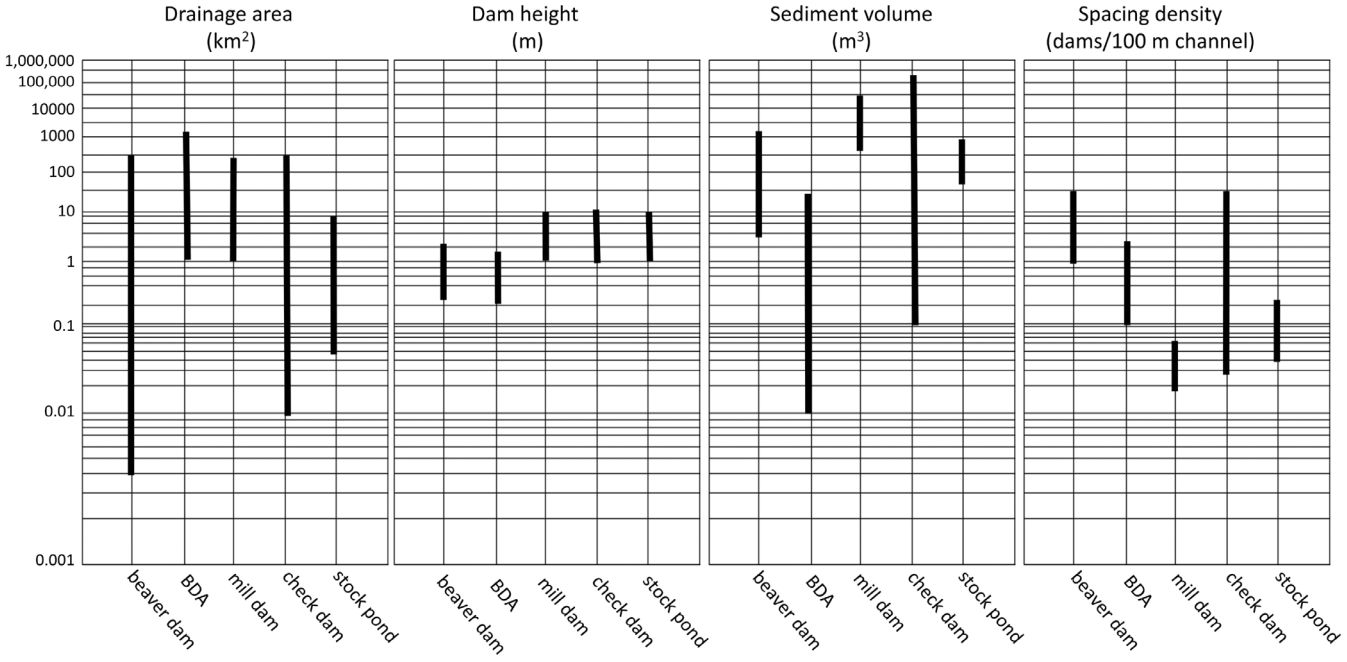

FIGURE 6 | Comparison of the published range of values for four attributes of small dams. Dark vertical lines indicate the range of values for each dam type listed on the x-axis for each attribute.

increase aquatic primary productivity and associated particulate organic matter derived from aquatic plants (Mendonça et al. 2012), causing increased rates of particulate organic matter deposition. Particulate organic matter transported into a dam backwater by a stream, as well as organic matter produced within the backwater, can influence organic carbon storage within the stream corridor. Burial in sediment sequesters organic carbon in backwaters (Mendonça et al. 2017), but a portion of the organic carbon deposited onto the sediment surface in the backwater will be mineralized to either CO_2 or CH_4 and emitted to the atmosphere via ebullition of CH_4-rich gas bubbles released from sediment or diffusive exchange between water and atmosphere at the water surface (Sobek et al. 2012). The balance between sequestration and emission depends on factors such as

- annual primary productivity within the backwater (a function of nutrient availability, light intensity, and mixing depth);
- diffusion rates in relation to water temperature, with greater rates typically observed for shallow water zones (Peeters et al. 2019);
- input fluxes of allochthonous dissolved and particulate organic carbon from the upstream catchment;
- mineralization fluxes (via contributions from biological respiration and photochemical degradation);
- sedimentation rates (Peeters et al. 2019); and
- organic carbon passing from the backwater downstream (Maavara et al. 2017).

Each of these controls can vary widely among individual dam backwaters, but oxygen availability near the backwater sediment appears to be a particularly important influence, with oxic conditions promoting emissions rather than sequestration (Carey et al. 2018). For large reservoirs, the balance between carbon source and sink depends on factors such as productivity in the water body, land use, geology, water body characteristics, and catchment morphometry (Phyoe and Wang 2019). Relatively higher organic carbon burial rates are predicted for lakes and reservoirs in warm and dry regions (Mendonça et al. 2017). It is difficult to generalize from the results of individual case studies of carbon balance in ponded waters because most of these studies come from large reservoirs or lakes.

Studies of beaver ponds indicate higher organic matter content in the sediment of older ponds (Butler and Malanson 1995) and in beaver ponds with finer sediment (Rees et al. 2024). Dissolved organic carbon in the backwater of beaver ponds becomes in part recalcitrant when buried in sediments and is thus sequestered (Gatti et al. 2018). Carbon can also be emitted from beaver ponds as methane and carbon dioxide but, as is the case with large reservoirs (Wang et al. 2019), there is no unified method for evaluating or predicting the balance of a ponded area as a carbon source versus a carbon sink.

In general, the ability of beaver dams to increase water levels in floodplains causes increased floodplain primary productivity and greater concentrations of organic carbon in floodplain soils, as well as carbon storage in pond sediments (Wohl et al. 2012; Wohl 2013; Johnston 2014; Laurel and Wohl 2019). Newly inundated surfaces increase the concentration of dissolved organic carbon in the water, but this carbon can be released into the atmosphere (e.g., Lazar et al. 2014; Smufer et al. 2023), especially where the water table is at or above the soil surface (Johnston 2017); sequestered by vegetation; or accumulated in sediment. The relative importance of these carbon pathways can vary by pond age (Gatti et al. 2018; Nummi et al. 2018). Consequently, present global estimates of the cumulative effect of beaver ponds range from a source to a sink for organic carbon (Nummi et al. 2018).

Few studies have been conducted thus far on the effects of beaver dam analogues on carbon dynamics in river corridors. Existing studies suggest the potential for enhanced carbon sequestration where beaver dam analogues are installed (Schultz 2023). Significant changes in sediment carbon stock, however, may require several years to develop (Hinshaw and Wohl 2023; Neace 2023).

Mill dams, like beaver dams, can have complicated effects on carbon dynamics. Comparing different former mill-dam backwaters, for example, Pearson et al. (2016) found that mill dams do not necessarily enhance floodplain sedimentation or carbon storage but promote brief periods of methane flux to the atmosphere. Other studies, however, indicate that the legacy sediments stored behind mill dams bury organic- and carbon-rich pre-dam sediments and therefore limit the ecological services, such as microbial cycling of elements, expected from these wetland soils (e.g., Walter and Merritts 2008; Weitzman et al. 2014; Peck et al. 2022, 2023). The fine-grained texture of sediments stored above mill dams could also potentially sorb and retain greater amounts of organic carbon compared to coarser sediments (Weil and Brady 2017) associated with beaver dams. Removal of the mill dam can facilitate channel erosion and the removal of carbon stored in sediment. Because most mill dams are no longer intact, the gaseous emissions of different forms of carbon from mill ponds have not received the level of attention given to beaver ponds.

Examination of soil organic carbon in sediments behind check dams indicates that sediment texture and distance from the channel head influence organic carbon concentrations, with decreasing concentrations at lower silt contents and greater distances from the channel head (Qin et al. 2022). The number of check dams, land use in the catchment, and climate also influence carbon storage at check dams (Lü et al. 2012). Limited studies from different catchments indicate that check-dam sediments can sequester organic carbon (Zhang et al. 2016; Mongil-Manso et al. 2019) or fail to do so relative to source soils (Liu et al. 2017; Yao et al. 2022). We were unable to find any studies of the effects of earthen embankments used for stock ponds on organic matter storage and carbon sequestration. However, by creating wetter zones with greater primary productivity and saturated soils, these embankments may create local carbon sinks along river networks.

In summary, the net effect of a dam on carbon dynamics will vary with the presence or absence of the dam and the associated

inundation of the backwater or exposure of backwater sediment. The net effect of the dam also varies with catchment- and pond-specific parameters. Consequently, generalizations regarding the cumulative effect of multiple dams within a catchment or region remain poorly constrained. However, the limited studies thus far indicate that beaver dams, beaver dam analogues, mill dams, and check dams can all increase carbon sequestration in fluvial sediments as long as the dam remains intact and ponding water. What is clearly needed now are more comprehensive studies that develop a complete carbon budget for a river corridor with one or more dams. This will facilitate comparison of the effects of different types of dams on carbon sequestration in sediment (or living organisms) versus gaseous emissions of carbon.

5.4 | Nutrients

Nutrients in river water include phosphorus (P) and nitrogen (N), which have received particular emphasis in studies examining problems related to excess nutrients. In general, the balances among water and elements or chemical compounds depend on

- water body temperature, solute chemistry, and water body geometry (shallow vs. deep) and residence time;
- sedimentation amount, rate, and texture, including potential vertical, lateral, and longitudinal patterns of sedimentation within the water body;
- sources of pore water in sediment, water flow paths, gradients, direction, and residence or travel time (Sherman et al. 2022), hyporheic and riparian groundwater exchange (Inamdar et al. 2022); and
- saturation or lack of saturation within the sediment.

Phosphorus in river corridors can be present in organic or inorganic forms and in dissolved or particulate forms (Records et al. 2016; Inamdar et al. 2020). The forms of most concern with respect to excess nutrients and water quality are soluble reactive P (orthophosphate) and phosphate sorbed onto clays. Phosphorus sorbed on clays travels with fine sediment and is thus typically stored in all types of dam backwaters (e.g., Maret et al. 1987 for beaver dams; Inamdar et al. 2022 for mill dam legacy sediments). The dynamics of soluble reactive P may be more complicated. A comparison of five beaver ponds in New York, USA, for example, revealed substantial differences in the effect of each pond on downstream P concentration in stream water, with three ponds increasing soluble reactive P during warmer months, one pond also increasing soluble reactive P during an extended period of ice cover, and two ponds consistently reducing downstream soluble reactive P at all times of the year (Klotz 1998). These results likely reflect the occurrence of anaerobic conditions and H_2S production at ponds that increase downstream soluble reactive P, although elevated levels of P occur for only short distances downstream (Klotz 1998). The ponds that did not increase downstream soluble reactive P had a stream channel that passed through the middle of the pond, bringing aerated water to most of the pond area and preventing the creation of sizeable anaerobic zones.

Soil total phosphorus concentrations in clay-rich sediment accumulated behind check dams in the Loess Plateau of China can be elevated relative to other soils in the catchment, indicating that the check dams create soil phosphorus sinks (Cheng et al. 2018). Increased phosphorus absorption in check-dam sediments has also been documented for sites in Iran (Asadzadeh et al. 2017) and Spain (Mongil-Manso et al. 2019).

Phosphorus dynamics in downstream waters can also be altered after dam removal exposes sediment accumulated in the backwater, especially in the case of mill dams, which tend to store greater volumes of fine-grained sediment than beaver dams. Riggsbee et al. (2012) discussed the role of plant immobilization of N and P from sediment, which is limited by the rate of plant colonization relative to the rate of sediment dewatering. If dewatering is faster than plant colonization, dam removal can create an initial release of N and P from a dewatered reservoir, with quantities influenced by the physical properties of the sediment, such as specific yield and porosity. Specifically, coarse sediment is typically nutrient-poor because low surface area limits availability for ion sorption and low porosity results in low interstitial water volume and rapid dewatering rates (Riggsbee et al. 2012). Mill-dam legacy sediments accumulated in streambanks can be a source or sink for P in streams, depending on stream water P concentrations and oxic/anoxic conditions in the bank (Inamdar et al. 2020).

As with P, N in streams can move in dissolved or particulate forms (Xia et al. 2018; Joshi et al. 2023). In the context of dams, the N forms of ammonium (NH_4^+) and nitrate (NO_3^-) receive the greatest attention (Akbarzadeh et al. 2019; Inamdar et al. 2021). Backwaters at beaver ponds typically store nitrate via microbial N fixation in pond sediment (Naiman and Melillo 1984) and in hyporheic exchange flows facilitated by the presence of a beaver dam (Lautz et al. 2006). This can lead to substantial reductions in downstream discharge of N (Maret et al. 1987; Correll et al. 2000; Klotz 2010), even in urban streams receiving sewer leaks (Ledford et al. 2023), although the magnitude of the effect can be greater on smaller streams (Bason et al. 2017). Beaver dam analogues can also create hyporheic exchange flows and N dynamics similar to those of natural beaver dams if a minimum hydraulic step height is exceeded (Wade et al. 2020).

The dynamic nature of oxic-anoxic soils, along with the organic, C-rich conditions upstream of beaver dams, can create favorable conditions for denitrification losses of nitrate-N (Larsen et al. 2021; Murray et al. 2023). Denitrification is the microbial process of reducing nitrate and nitrite to gaseous forms of nitrogen (Tiedje 1988; Giles et al. 2012). Denitrification may be the largest net remover of N in some beaver ponds (e.g., Bason et al. 2017) but may be relatively low in others (e.g., Lazar et al. 2014).

For mill dams with less dynamic hydrology than beaver systems, the effects on N dynamics for existing and removed dams are complex (e.g., Lewis et al. 2021; Inamdar et al. 2021; Inamdar et al. 2022; Peck et al. 2022; Sherman et al. 2022). Although natural riparian zones with variable water levels can be ideal environments for coupled nitrification–denitrification N removal (Lowrance et al. 1997), the same may not be true for riparian

systems upstream of existing mill dams (Inamdar et al. 2022; Inamdar et al. 2024). Stagnant water levels and persistent anoxic conditions may depress nitrification, reduce denitrification (Peck et al. 2022), and favor the occurrence of competing reductive N processes such as dissimilatory nitrate reduction to ammonium (DNRA, Burgin and Hamilton 2007). Depression of nitrification and the occurrence of DNRA result in retention of N as ammonium-N (Tiedje 1988; Inamdar et al. 2022). In addition, highly reducing soils associated with mill dams enhance the reductive dissolution of iron, with subsequent release of organic carbon and nitrogen (Pan et al. 2016).

On the other hand, mill dam removals can reinstate the dynamic groundwater hydrologic conditions but also result in tall, drained, and oxic riparian terrace soils (Merritts et al. 2011; Lewis et al. 2021). These drained soils could facilitate oxidation of the buried organic C and N and nitrification of the stored ammonium-N, resulting in a release of nitrate to drainage waters (Weitzman and Kaye 2017; Weitzman et al. 2014). This nitrate could be released to stream waters or potentially intercepted by anoxic soil conditions closer to the groundwater interface and removed by denitrification N processes (Lewis et al. 2021). The net effect of mill dams on N dynamics is thus complex, difficult to quantify, and highly dependent on site-specific characteristics (Inamdar et al. 2024).

Check dams and stock ponds have not received as much attention as beaver or mill dams with regard to N and P dynamics. As in the case of P, sediment accumulated behind check dams can have high concentrations of soil N and create N sinks (Mongil-Manso et al. 2019), although some studies indicate that check-dam construction induces a net N loss relative to source soils, likely as a result of carbon oxidation during erosion from the source areas and deposition behind the check dam (Liu et al. 2017). The differences among studies appear to relate to what type of soils are compared to the check-dam sediments (e.g., forest, grassland, or agricultural soils), with soils under native land cover typically enriched in N relative to check-dam sediments. Differences among studies may also relate to distance downstream, with check dam sediments farther from channel heads containing less nitrogen (Qin et al. 2022).

In summary, it is clear that the size of the dam and the nature of the groundwater table (static or dynamic) have important consequences for the cycling and fate of nutrients associated with beaver and human-made dams. Beaver dams appear to facilitate hyporheic exchange and backwater sedimentation, with the net effect of reducing P and N concentrations downstream from most dam-pond pairs. Existing mill dams could have more complex effects. Removal of these dams could facilitate more natural conditions that may be favorable for nutrient removals. Some check dams provide P and N sinks, whereas others do not.

5.5 | Habitat

The backwater upstream from a dam can increase aquatic habitat diversity within a river corridor (e.g., Wright et al. 2002; Smith and Mather 2013) by altering the abundance and distribution of water depth, velocity, clarity, temperature, and dissolved oxygen and nutrients, as well as the characteristics of bed substrate (grain size distribution, stability, nutrient content) (e.g., Graeb et al. 2009; Smith and Mather 2013; Beall et al. 2022). Dams can also fragment habitats and reduce connectivity within and along a river corridor by creating barriers to migration and dispersal for some species such as riparian vegetation that relies on hydrochory for propagule dispersal downstream (Jansson et al. 2000), fish that cannot pass upstream or downstream beyond dams (Liermann et al. 2012), or juvenile aquatic insects that rely on downstream drift for dispersal (Abernethy et al. 2023). Most of these restrictions on species movement caused by dams have been documented for large dams, rather than the small dams that are the focus here, but even a relatively small, impermeable mill or check dam can restrict species movement (e.g., Hall et al. 2011). The net effect of a dam or series of dams on habitat abundance and accessibility varies with the number and size of the dams and their backwaters, as well as the species under consideration and their dispersal abilities and specific habitat needs (Poff and Hart 2002). Similarly, the abundance and diversity of lotic (flowing water), lentic (ponded water), and riparian habitat depend on the area, volume, and age distribution of the backwaters created by dams (e.g., Ray et al. 2001; Graeb et al. 2009).

In general, beaver dams and ponds are noted as substantially increasing habitat for a wide array of aquatic, riparian, and terrestrial species (Larsen et al. 2021; Grudzinski et al. 2022; Wilson and Bremner-Harrison 2025), including bacterial and archaeal communities (Shannon et al. 2023), aquatic and riparian plants (Willby et al. 2018), aquatic macroinvertebrates (Hood and Larson 2014; Law et al. 2016), native fishes (Smith and Mather 2013), amphibians (Romansic et al. 2021), reptiles (Russell et al. 1999), riparian birds, waterfowl, wading birds, and raptors (Aznar and Desrochers 2008; Fedyń et al. 2024), and both small (Sundell et al. 2021) and large (Nummi et al. 2019) mammals. The important aspects of beaver modifications that lead to these benefits are (i) the diverse habitats on and within beaver dams (e.g., Rolauffs et al. 2001), beaver lodges (e.g., Wilson and Bremner-Harrison 2025), beaver ponds with varying degrees of hydrologic connectivity and infilling by sediment, and beaver canals (Grudzinski et al. 2020), (ii) the permeability and alternative pathways around beaver dams, which limit their effects on longitudinal movements by organisms, and (iii) the transient nature of at least some beaver dams relative to most small, human-built dams. We have observed beaver dams that repeatedly breach and are rebuilt over a period of multiple years, as well as beaver dams that remain intact for multiple years. Overall, beaver activities increase the diversity of habitats present within a riverine habitat mosaic (Stanford et al. 2005) and greatly increase the abundance of some habitats such as submerged wood and secondary channels.

Although a smaller literature documents the effects of beaver dam analogues on habitat abundance and diversity, the basic effects of beaver dam analogues in creating lentic habitat, side channels with hydraulic, thermal, and substrate diversity, and increased organic matter accumulation replicate those of beaver dams (e.g., Corline et al. 2023). However, direct comparisons of beaver dams and beaver dam analogues suggest that beaver dam analogues modify habitats in a way that only partially replicates modifications associated with natural beaver dams (Wolf and Hammill 2023). This may partly reflect the relative recency of

beaver dam analogue emplacement relative to the length of time that analogous natural beaver dams have been present along a river corridor (Wolf and Hammill 2023).

Searches for literature on the effects of other types of dams on habitat diversity do not result in nearly as long a list of studies as those for beaver dams. Among the dam types considered here, mill and check dams and ponds likely add the least habitat diversity to river corridors, based on the relative paucity of published research on this topic. Mill dams can provide lentic habitat for aquatic macroinvertebrates (Wood and Barker 2000; Hill et al. 2017), especially in regions with extensive loss of natural ponds and wetlands as a result of agricultural and urban land uses. The presence of old mill ponds in relatively urbanized regions, however, can limit their effectiveness as habitat. Habitat effectiveness of these ponds depends on factors such as surface area, depth, banks and margins, shade, shoreline irregularity, water quality, presence of invasive species, and proximity to other wetlands or green spaces (Oertli and Parris 2019).

Check dams can create wet meadow and riparian vegetation habitat by storing relatively moist and fine-grained sediment along valley-floor margins (e.g., Bombino et al. 2014; Hartman et al. 2016; Zema et al. 2018). By altering water and sediment fluxes downstream, check dams can create aquatic habitat diversity, although it is not clear how this relates to habitat diversity in otherwise analogous, undammed streams (Shieh et al. 2007). Mill and check dams also create the greatest limitations to longitudinal connectivity of habitat. Most organisms seem to have little trouble moving around beaver dams (Pollock et al. 2022). Stock-pond habitat in drylands is likely to be used by wetland species that can move between ponds (e.g., frogs, waterfowl). Mill and check dams, however, commonly limit longitudinal movements by aquatic species such as fishes in relatively low-relief environments such as the coastal eastern United States (Hall et al. 2011; Hogg et al. 2015), in which native fishes never had to adapt to tall barriers along their migration routes. In some regions, mill or check dams are simply too tall to allow fish passage (e.g., Nagayama et al. 2020).

Stock ponds can create lentic and wetland habitat in otherwise relatively dry environments, and this can benefit biota including aquatic invertebrates (Hale et al. 2015), amphibians (Peltzer et al. 2006), wetland birds (May et al. 2002), and waterbirds, especially where large ponds support structural diversity of vegetation and shoreline topography and water depth (Froneman et al. 2001). However, this habitat can also support non-native vertebrate predators (frogs, fishes) of aquatic invertebrates (Hale et al. 2015). As described by Hale et al. (2015), stock ponds differ from naturally occurring perennial stream pools in drylands in that stream pools experience more severe flooding, erosion, and deposition and are smaller than stock ponds. These characteristics can support different species distributions in stock ponds and natural pools in drylands.

In summary, the large array of studies on beaver-modified river corridors, as well as the details of those studies, suggests that beaver dams are more effective than human-built dams at creating diverse and abundant habitat within river corridors. Beaver dam analogues, mill dams, check dams, and stock ponds can also provide beneficial increases in habitat abundance and diversity, but these are much less well documented than those associated with beaver dams and appear to be less consistent between sites and with respect to favoring native versus introduced biota. The key differences between beaver dams and human-built dams with respect to habitat appear to be related to two factors. First, beaver dams typically do not create impermeable barriers to the movement of surface and subsurface water, dissolved nutrients, sediment, and particulate organic matter. This reflects the tendency of beaver dams to fail or be abandoned and fall into disrepair, as well as the fact that dams are not necessarily present on the main channel in a river corridor but can be present on secondary channels, tributaries, and seeps or springs associated with groundwater upwelling or hyporheic return flows across the floodplain. Second, multiple beaver dams and ponds of differing ages and habitat characteristics can be present in a beaver-modified river corridor. In contrast, human-built dams are more likely to create persistent, impermeable barriers placed in consistent locations perpendicular to flow in the main channel that result in limited increases in habitat abundance and diversity relative to undammed conditions. The detailed effect of any dam—beaver or human-built—depends on both dam characteristics and the effects of the dam relative to undammed conditions at that particular site, but the effects of beaver dams on aquatic and riparian habitat have received more attention than the effects of small, human-built dams.

5.6 | Biota

The effects of a dam on individual species and biotic communities are analogous to the effects on habitat in that dams and their backwaters can favor species that prefer ponded water and aquatic-riparian edge habitat and thus potentially increase biomass and biodiversity within a river corridor (e.g., Wright et al. 2002; Law et al. 2016; Barnett and Adams 2021). Conversely, dams and backwaters can also limit organism dispersal longitudinally along a river corridor and thus decrease biomass and biodiversity (e.g., Sor et al. 2023). The net effects vary with the number and size of the dams and backwaters and the species under consideration (e.g., Kanehl et al. 1997; Li et al. 2013). As noted for habitat, the majority of published studies of the effects of dams on aquatic and riparian biota focus on larger dams.

Studies of the effects of beaver modifications on biota tend to focus on the abundance of a single species or group of related species, such as frogs, or on the effects of beaver on river corridor biodiversity of a group of organisms, such as aquatic macroinvertebrates. These types of studies indicate that beaver modifications nearly always increase the abundance of species targeted for study and the biodiversity of organism groups, including wetland (Willby et al. 2018) and riparian plants (Wright et al. 2002), aquatic (Hood and Larson 2014; Law et al. 2016; Nummi et al. 2021) and terrestrial invertebrates (Bush et al. 2019), fishes (Smith and Mather 2013; Bylak et al. 2014), amphibians and reptiles (Russell et al. 1999; Hossack et al. 2015; Romansic et al. 2021), birds (Orazi et al. 2022; Fedyń et al. 2024), and terrestrial and semi-aquatic mammals (Nummi et al. 2019; Sundell et al. 2021; Graham and Goodenough 2024; Hooker et al. 2024; Wikar et al. 2024). There are, however, examples of beaver ponds enhancing the abundance of non-native species (Gibson et al. 2015).

There has been controversy around the topic of whether beaver dams impede fish passage and thus the distribution, abundance, and diversity of fishes (e.g., Burchsted et al. 2010; Kemp et al. 2012). Although the consensus is gradually shifting toward the net positive effects of beaver dams on fishes (e.g., Pollock et al. 2022), the effects of beaver dams on fish passage provide an example of the nuances of dam effects on biota. Examining the effects of beaver dams on salmonid passage in tributary catchments of the Logan River, Utah, USA, Lokteff et al. (2013) found that beaver dams do not impede the movement of native cutthroat trout (*Oncorhynchus clarkii utah*) and nonnative brook trout (*Salvelinus fontinalis*) but impede the movements of some individuals among invasive brown trout (*Salmo trutta*). Physical characteristics of the dams, including height and upstream location, as well as flow stage, affected the ability of salmonids to pass dams, with brown trout hindered by low flows. Two important considerations for fish passage in beaver-dammed stream corridors are that (i) beaver dams frequently breach or partly breach at least temporarily and (ii) in a wide stream corridor, other hydrologic pathways such as beaver canals may facilitate fish movement around, rather than over, beaver dams (Cutting et al. 2018). Beaver dams in Nova Scotia, Canada, for example, did not prevent upstream fish passage in most years, but did limit (but not prevent) passage during dry years until the beaver dam complex failed naturally (Taylor et al. 2010).

Almost no peer-reviewed studies have yet been published that evaluate the effects of beaver dam analogues on any aspect of biotic abundance or diversity. An exception is Wolf and Hammill (2023), which found that beaver dam analogues support greater abundance and diversity of amphibians and fishes than are found in undammed (unrestored) stream reaches, although abundance and diversity values are generally less than those in beaver-modified stream corridors. As the abundance of beaver dam analogues and the time since their emplacement both increase, presumably the literature documenting their effects on biota will expand.

The literature on biomass and biodiversity in the context of mill dams predominantly focuses on increases in upstream fish biomass and biodiversity following the removal of a mill dam (e.g., Doucette 2009; Hogg et al. 2015; Livermore et al. 2017). Mill ponds and tailraces can provide good habitat for freshwater mussels (Singer and Gangloff 2011; Hoch 2012; Ahlstedt et al. 2017), although drought conditions can create complete mortality of mussels in water-mill canals, in contrast to mussel populations in nearby natural channels (Sousa et al. 2019). Simmons (2024) found that sites upstream from mill dams in Indiana, USA, had greater turtle diversity than sites downstream. What is perhaps most noticeable is the highly limited number and range of peer-reviewed studies on mill dams and biota relative to the number of studies on beaver dams and biota.

As noted previously, check dams can trap sediment that provides suitable habitat for riparian vegetation and comparisons of channel reaches with and without intact check dams indicate higher riparian vegetation biomass around check dams in southern Italy (Ricci et al. 2019) and South Africa (Schmiedel et al. 2017), and greater vegetation diversity around check dams in southeastern Spain (González-Romero et al. 2019). In this context, it is important to remember that check dams are preferentially placed in eroding river corridors that may have limited riparian vegetation habitat away from the dammed areas. Investigation of aquatic macroinvertebrate functional feeding groups in a stream in Thailand indicated a shift toward collector-gatherers in the fine sediment accumulation above dams and a shift toward predators in dam ponds (Suriyawong et al. 2018), which the investigators interpreted as "disturbing functional feeding group distribution [in a way] that can lower stream functions" (1384). Removal of check dams can increase upstream fish abundance (Chang et al. 2017), as found for removal of mill dams. On balance, check dams can increase riparian biomass and biodiversity in eroding channels but can also decrease upstream aquatic organism passage and associated biomass and biodiversity. The details of check dam design also matter. Comparison of traditional check dams, morphologically based artificial steps using large boulders, and unmodified mountain streams in Italy indicated that natural streams had the highest aquatic macroinvertebrate taxa richness and diversity, whereas traditional check dams had the lowest (Comiti et al. 2009).

Stock ponds tend to be fairly small, deep, and steep-sided relative to natural water bodies and therefore contain less shallow edge habitat (Brock et al. 1999). Stock ponds can nonetheless support aquatic macroinvertebrates and aquatic macrophytes (Markwell and Fellows 2008), as well as frogs (Hazell et al. 2004) and waterbirds (Froneman et al. 2001). Stock ponds can thus help to maintain regional biodiversity in heavily managed catchments (Chester and Robson 2013), although details such as the structural diversity of vegetation in and around the ponds exert a critical influence on the biomass and biodiversity of aquatic and other animals (e.g., Froneman et al. 2001). Fish, amphibian, and crayfish abundance in stock ponds in the North American prairie, for example, varied in relation to pond size, water permanency gradient, and interactions among species: smaller and less permanent ponds were dominated by crayfish and amphibians whereas larger ponds were dominated by stocked sportfish, which tended to reduce the numbers of other organisms such as amphibians (Pfaff, Hase, and Gido 2023). It is worth noting that the studies documenting organisms supported by stock ponds consistently stressed the importance of maintaining natural water bodies, which can support slightly different species assemblages than those in stock ponds (e.g., Hazell et al. 2004). As for the other types of small, human-built dams considered here, there is a comparative dearth of peer-reviewed literature on the effects of stock ponds on biomass and biodiversity.

In summary, beaver modifications of river corridors in the form of dams, ponds, canals, and lodges appear to consistently promote biomass and biodiversity by creating a much greater diversity of aquatic and riparian habitats and by posing little limitation to longitudinal movements by organisms. The very limited studies published thus far on beaver dam analogues suggest that they may create some of the same benefits for biota provided by beaver dams, although typically to a lesser degree that may partly reflect the relatively recent implementation of beaver dam analogues as part of river management. Mill dams can support greater biomass and diversity of freshwater mussels but can also limit upstream fish populations. Check dams commonly increase the biomass of riparian vegetation but can limit the abundance of aquatic macroinvertebrates and fishes. Stock ponds can increase biomass and diversity of aquatic macroinvertebrates,

amphibians, and waterbirds, although the details of pond configuration can strongly influence these effects. More studies are needed that compare biomass and biodiversity associated with small, human-built dams relative to biomass and biodiversity in analogous undammed portions of river corridors.

5.7 | Integrated Effects

The alterations associated with any particular dam depend strongly on site-specific interactions. Backwater volume, for example, will reflect valley geometry and dam height, as well as water and sediment inflows and outflows and, for water, evaporation and infiltration from the backwater. Backwater and sediment chemistry will reflect water temperature and biotic alterations via organisms within the water column and in the sediment. Nitrate uptake, as a specific example, depends on backwater sediment grain-size distribution, water temperature, and dissolved oxygen levels, microbial and aquatic macrophyte communities, water residence time, nitrate concentration, and hyporheic and/or groundwater exchanges (James et al. 2008; Kreiling et al. 2011; Yang et al. 2021).

The site-specific interactions among numerous potential control variables make it challenging to quantify or predict the effects of any specific dam, as well as the cumulative effects of numerous dams or series of dams within a catchment. Studies that have begun to address integrated effects and the cumulative effects of sequential dams, however, indicate that even small dams can have substantial effects. Quantifying the spatial extent of altered wetted width and channel substrate caused by six low-head (1.2–3 m tall) dams along the Neosho River, Kansas, USA, for example, Fenci et al. (2015) found that the dams impacted more than 47 km of river length, with each dam affecting, on average, 7.9 km of channel. In this analysis, the number of upstream dams and distance to upstream dams, but not dam height, affected the spatial extent of dam-induced alterations. More studies that consider the cumulative effects of sequential dams of different types would greatly facilitate the evaluation of net ecosystem benefits or costs of such dams.

6 | Beaver Versus Human Dams: A Synthesis

Table 1 summarizes the basic characteristics of beaver dams and human dams. Figure 6 provides ranges of commonly reported parameters from existing literature (see also Table S1). Beaver dams, beaver dam analogues, and mill and check dams allow water flow over the top of the dam, at least during high river stages. Beaver dams and beaver dam analogues are also likely to be at least slightly porous and permeable and thus allow flow through the dam. Embankment ponds are typically earth-fill structures and are designed to be impermeable and resist overtopping. Human dams are commonly intended to persist for years to decades. Individual beaver dams can persist for decades but are more likely to be used for only a few years before the beavers move to another site in the stream corridor. One implication of this transience is the presence of multiple abandoned beaver dams and ponds with differing stages of infilling and water quality that increase habitat and biodiversity (Snodgrass and Meffe 1998; Bonner et al. 2009; Sferra et al. 2017).

Human-built beaver dam analogues, mill dams, check dams, and earthen embankments are intended to create a single dam with a backwater, although there can be multiple dams in sequence along a stream. As noted earlier, beavers build dams with diverse orientations relative to the general downstream trend, and many of these dams may not be on the mainstem channel. Beaver dam analogues may follow these patterns but are more likely to be similar to other human-built dams with regard to being in sequence on the mainstem. As noted with respect to fish passage, beaver dams are more likely than human-built dams (except for beaver dam analogues) to have secondary channels that flank the dam and provide surface hydrologic connectivity within the stream corridor.

One effect of beaver dams with variable orientation and location is to substantially increase the patchiness of the river corridor. Patches are discrete spatial units that differ from adjacent units. The patchiness of the river corridor describes the three-dimensional spatial heterogeneity of the corridor (Ward et al. 1999; Beechie et al. 2006). Different criteria can be used to delineate patches. In river corridors, patches typically differ based on topography and vegetation community, which reflect the geomorphic history of fluvial erosion and deposition, grain-size distribution, soil moisture, and residence time of the underlying substrate (Iskin and Wohl 2023). Disturbances such as floods and fire alter the distribution of patches through time, as expressed in the shifting habitat mosaic (Arscott et al. 2002; Stanford et al. 2005). The transience of individual beaver dams can also create a shifting habitat mosaic, especially in a beaver meadow.

Human-built dams other than beaver dam analogues are likely to impede fish passage. Hart (2004), for example, described fishermen obtaining legislation to remove or modify mill dams that prevented migratory fish from reaching their spawning grounds in 18th-century America. However, backwaters associated with human dams may benefit other types of aquatic organisms. Stock ponds in relatively dry regions are commonly built on ephemeral or intermittent channels, and the ponds vary from intermittently wetted to perennial. Aquatic organisms may not be present in these stream networks, or the ponds may create refuge pools and additional habitat for aquatic species such as invertebrates and amphibians (e.g., Hale et al. 2015; Mims et al. 2020, 2023) and for wetland birds (May et al. 2002). Stock ponds can provide ecosystem benefits where consumptive water use or climate change in drylands has reduced the abundance of ponded water and wetlands in river corridors. Mill ponds, even in regions with abundant surface water (e.g., England) may provide rare lentic habitat along stream corridors and support populations of organisms such as amphibians that prefer such habitat (Wood and Barker 2000). Mill ponds can provide ecosystem benefits where stream corridor engineering in wetter regions has reduced the presence of naturally occurring river-wetland corridors (Wohl et al. 2021).

Each of the five types of dams considered here can alter river corridors and river networks in ways that persist for decades to millennia. As long as the dams themselves remain intact, they can impede the downstream passage of materials and, in some cases, longitudinal movements by organisms. After the dams are breached, the remaining ponded sediment can alter river corridor morphology and habitat upstream from the dam, as

well as supplies of solutes and particulate material (sediment, organic matter) to downstream portions of the river network.

Figure 7 conceptually illustrates the relative magnitude and benefits of these persistent alterations. Although the assessments of benefits and costs in this figure are qualitative, they are informed by available knowledge as reflected in peer-reviewed papers summarized here. These assessments lead us to order small dams from generally most beneficial (beaver meadows with multiple dams) to least beneficial (mill dams), recognizing that beaver meadows may not be beneficial at some sites for infrastructure and human property within the river corridor, and mill dams may be beneficial at some sites where they impede upstream migration by invasive species (Gangloff 2013) or provide lentic habitat in the river corridor.

7 | Conclusions

Despite numerous case studies on the local effects of individual small dams of different types, river scientists and managers cannot yet quantitatively predict the diverse catchment-scale effects of adding (e.g., beaver dam analogues) or removing (e.g., mill dams) multiple small dams. The hydrologic effects of numerous smaller storage structures used in natural flood management in the United Kingdom are just starting to be quantitatively evaluated using numerical models (Hill et al. 2023; Follett et al. 2024), however, we expect that this type of quantitative, catchment-scale, model-based analysis will soon be extended to natural beaver dams and small, human-built dams. At present, beaver reintroduction and construction of beaver dam analogues are occurring in catchments throughout the conterminous United States, the United Kingdom, and Europe as a means of promoting catchment resilience to the increasing frequency and magnitude of disturbances, including floods, droughts, and wildfires. Earthen embankments continue to be constructed in drylands to increase resilience to drought. Check dams continue to be constructed, primarily for erosion control. Mill dams are mostly being removed to increase longitudinal connectivity and fish passage and to improve safety or are falling apart without human intervention to maintain aging dams.

To some extent, these interventions of building or removing dams represent reach- to catchment-scale experiments, but such experiments can enhance understanding and management only if river scientists and managers monitor associated changes in water, nutrients, particulate matter, habitat, and biota. Site-specific monitoring—case studies—is critical to developing the data that can inform and validate catchment-scale numerical models and predictions. The limited number of citations for some of the dam-related effects discussed in this paper reflects the dearth of published information that we were able to find on these topics. Specifically, we identified research gaps that include: (i) the effects of mill dams, remnant mill-pond sediments, check dams, and dryland earthen embankments on local hyporheic exchange and local and downstream groundwater recharge; (ii) the net effect of any type of dam or sequence of dams on either the water balance or the carbon balance of a river corridor, as reflected in backwater storage, groundwater recharge, hyporheic exchange, evaporation, transpiration, and base and peak flows for water balance, and storage of dissolved and particulate inputs from upstream and from adjacent uplands, storage of dissolved and particulate carbon, gaseous emissions, altered primary productivity in the river corridor, and downstream outputs of dissolved and particulate carbon for carbon balance; (iii) the effects of earthen embankments on phosphorus and nitrogen dynamics; and (iv) the reach- to catchment-scale cumulative effects of multiple, sequential dams on any of the ecosystem

	beaver meadows	single beaver dam	single beaver dam analogue	earthen embankment	check dam	mill dam
Benefits						
Water storage	+++	+	+	++	+	+
Sediment storage	+++	+	+	++	++	++
Nutrient storage & uptake	+++	+	+	+	+	+
Habitat abundance & diversity	+++	+	+	++	+	+
Biomass & biodiversity	+++	+	+	++		+
Restrict invasive species mobility					+	+++
Carbon storage	+++	+	+		+	++
Costs						
Downstream water deficit				-		
Downstream channel erosion				-	- -	-
Downstream excess sediment/nutrients (after breaching)					-	- - -
Gaseous C emissions	-	-	-			-
Reduced longitudinal biotic connectivity		-	-		- -	- - -
Support non-native vertebrate predators				-		

FIGURE 7 | Illustration of the net benefits and costs of different types of dams considered in this paper. The types of dams are ordered by relative benefit from left to right, with the most beneficial on the left. The number of + symbols under benefits and – symbols under costs indicate the likely magnitude of the effect, from + or – for small effect to +++ or ––– for substantial effect. The inset photo for the earthen embankment is a Google Earth view (with scale bar) for a stock pond in Wyoming.

services considered here (water, nutrients, sediment, particulate organic matter, habitat, biota).

We did not evaluate how effective different types of human-built dams are at achieving their intended purposes. Rather, we evaluated their potential ecosystem effects relative to beaver dams with the purpose of estimating whether small human-built dams can provide ecosystem services analogous to those provided by beaver dams. Our analysis suggests that beaver dams, and to a lesser extent beaver dam analogues, have a higher benefit/cost ratio than human-built dams with respect to ecosystem services, especially in intermittent to perennial streams. The benefits of multiple beaver dams and ponds seem to arise primarily from: (i) the simultaneous presence of dam-pond pairs of differing ages that maximize habitat diversity and provide migration pathways and refugia for diverse organisms; (ii) the enhanced storage of surface and subsurface water, sediment, nutrients, and organic matter that results from maximizing lateral and vertical connectivity across the entire river corridor, while limiting longitudinal connectivity; and (iii) the redundancy of multiple dams and ponded areas, which can reduce peak flows and sediment transport if one dam fails. The inability of beavers to dam large rivers suggests that management designed to protect and enhance the benefits created by beaver modifications of river corridors should be targeted at relatively small streams and at as many sites as feasible within the context of a larger river catchment to substantially enhance catchment-scale resilience to disturbance (Wohl 2024).

Author Contributions

Ellen Wohl: conceptualization (equal), writing – original draft (equal). **Shreeram Inamdar:** writing – review and editing (equal).

Acknowledgments

This overview received no external funding. We thank Shayla Triantafillou and two anonymous reviewers for helpful comments on an earlier draft of the manuscript. We also thank the many people who have asked how other small dams compare to beaver dams after one of the first author's talks on beaver ecosystem engineering.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No original data were developed for this overview article.

Related WIREs Articles

Little dams, big problems: The legal and policy issues of nonjurisdictional dams

Beaver: Nature's ecosystem engineers

Identifying anthropogenic legacy in freshwater ecosystems

References

Abernethy, E. F., J. D. Muehlbauer, T. A. Kennedy, et al. 2023. "Population Connectivity of Aquatic Insects in a Dam-Regulated, Desert River." *River Research and Applications* 39: 364–374. https://doi.org/10.1002/rra.3972.

Agoramoorthy, G., S. Chaudhary, P. Chinnasamy, and M. J. Hsu. 2016. "Harvesting River Water Through Small Dams Promote Positive Environmental Impact." *Environmental Monitoring and Assessment* 188: 645. https://doi.org/10.1007/s10661-016-5640-5.

Ahlstedt, S. A., J. R. Powell, R. S. Butler, et al. 2017. "Historical and Current Examination of Freshwater Mussels (Bivalvia: Margaritiferidae: Unionidae) in the Duck River Basin, Tennessee, USA." *Malacological Review* 45: 1–163.

Akbarzadeh, Z., T. Maavara, S. Slowinski, and P. Van Cappellen. 2019. "Effects of Damming on River Nitrogen Fluxes: A Global Analysis." *Global Biogeochemical Cycles* 33: 1339–1357. https://doi.org/10.1029/2019GB006222.

Albinia, A. 2010. *Empires of the Indus: The Story of a River*. W.W. Norton & Co.

Angelakis, A. N., M. Valipour, J. Dietrich, et al. 2022. "Sustainable and Regenerative Development of Water Mills as an Example of Agricultural Technologies for Small Farms." *Water* 14: 1621. https://doi.org/10.3390/w14101621.

Armanini, A., F. Dellagiacoma, and L. Ferrari. 1991. *Fluvial Hydraulics of Mountain Regions*, edited by A. Armanini and G. Di Silvio, 331–344. Springer-Verlag.

Arscott, D. B., K. Tockner, D. Van der Nat, and J. V. Ward. 2002. "Aquatic Habitat Dynamics Along a Braided Alpine River Ecosystem (Tagliamento River, Northeast Italy)." *Ecosystems* 5: 802–814. https://doi.org/10.1007/s10021-002-0192-7.

Asadzadeh, F., S. M. A. Abbasian, and A. Samadi. 2017. "Phosphorus Adsorption Behavior in the Sediments Behind Successive Sedimentation Dams." *Journal of Natural Environment* 70: 1–14. https://doi.org/10.22059/jne.2017.128420.959.

Aznar, J. C., and A. Desrochers. 2008. "Building for the Future: Abandoned Beaver Ponds Promote Bird Diversity." *Ecoscience* 15: 250–257. https://doi.org/10.2980/15-2-3107.

Baker, B. W., and E. P. Hill. 2003. "Beaver." In *Wild Mammals of North America: Biology, Management, and Conservation*, edited by G. A. Feldhamer, B. C. Thompson, and J. A. Chapman, 2nd ed., 288–310. Johns Hopkins University Press.

Barnett, Z. C., and S. B. Adams. 2021. "Review of Dam Effects on Native and Invasive Crayfishes Illustrates Complex Choices for Conservation Planning." *Frontiers in Ecology and Evolution* 8: 621723. https://doi.org/10.3389/fevo.2020.621723.

Barraud, R. 2017. "Removing Mill Weirs in France: The Structure and Dynamics of an Environmental Controversy." *Water Alternatives* 10, no. 3: 796–818.

Bason, C. W., D. E. Kroes, and M. M. Brinson. 2017. "The Effect of Beaver Ponds on Water Quality in Rural Coastal Plain Streams." *Southeastern Naturalist* 16: 584–602. https://doi.org/10.1656/058.016.0408.

Beall, C. C., M. D. Dixon, N. D. Illeperuma, M. R. Sweeney, and W. C. Johnson. 2022. "Expansion of Woody Vegetation on a Missouri River Reservoir Delta-Backwater." *Ecohydrology* 15: e2357. https://doi.org/10.1002/eco.2357.

Beechie, T. J., M. Liermann, M. M. Pollock, S. Baker, and J. Davies. 2006. "Channel Pattern and River-Floodplain Dynamics in Forested Mountain River Systems." *Geomorphology* 78: 124–141. https://doi.org/10.1016/j.geomorph.2006.01.030.

Bigler, W., D. R. Butler, and R. W. Dixon. 2001. "Beaver-Pond Sequence Morphology and Sedimentation in Northwestern Montana." *Physical Geography* 22: 531–540. https://doi.org/10.1080/02723646.2001.10642758.

Bishop, P., and E. Muñoz-Salinas. 2013. "Tectonics, Geomorphology and Water Mill Location in Scotland, and the Potential Impacts of Mill Dam Failure." *Applied Geography* 42: 195–205. https://doi.org/10.1016/j.apgeog.2013.04.010.

Bishop, P., E. Muñoz-Salinas, A. B. MacKenzie, I. Pulford, and J. McKibbin. 2010. "The Character, Volume and Implications of Sediment Impounded in Mill Dams in Scotland: The Case of the Baldernock Mill Dam in East Dunbartonshire." *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* 101: 97–110. https://doi.org/10.1017/S1755691010009205.

Bombino, G., G. Barbaro, D. D'Agostino, P. Denisi, A. Labate, and S. M. Zimbone. 2022. "A Method for Estimating Stored Sediment Volumes by Check Dam Systems at the Watershed Level: Example of an Application in a Mediterranean Environment." *Journal of Soils and Sediments* 22: 1329–1343. https://doi.org/10.1007/s11368-022-03163-6.

Bombino, G., C. Boix-Fayos, A. M. Gurnell, V. Tamburino, D. A. Zema, and S. M. Zimbone. 2014. "Check Dam Influence on Vegetation Species Diversity in Mountain Torrents of the Mediterranean Environment." *Ecohydrology* 7: 678–697. https://doi.org/10.1002/eco.1389.

Bombino, G., A. M. Gurnell, V. Tamburino, D. A. Zema, and S. M. ZImbone. 2007. "A Method for Assessing Channelization Effects on Riparian Vegetation in a Mediterranean Environment." *River Research and Applications* 23: 613–630. https://doi.org/10.1002/rra.1004.

Bombino, G., A. M. Gurnell, V. Tamburino, D. A. Zema, and S. M. Zimbone. 2008. "Sediment Size Variation in Torrents With Check Dams: Effects on Riparian Vegetation." *Ecological Engineering* 32: 166–177. https://doi.org/10.1016/j.ecoleng.2007.10.011.

Bonner, J. L., J. T. Anderson, J. S. Rentch, and W. N. Grafton. 2009. "Vegetative Composition and Community Structure Associated With Beaver Ponds in Canaan Valley, West Virginia, USA." *Wetlands Ecology and Management* 17: 543–554. https://doi.org/10.1007/s11273-009-9131-0.

Brazier, R. E., A. Puttock, H. A. Graham, R. E. Auster, K. H. Davies, and C. M. L. Brown. 2021. "Beaver: Nature's Ecosystem Engineers." *Wiley Interdisciplinary Reviews Water* 8, no. 1: e1494. https://doi.org/10.1002/wat2.1494.

Brock, M. A., R. G. B. Smith, and P. J. Jarman. 1999. "Drain It, Dam It: Alteration of Water Regime in Shallow Wetlands on the New England Tableland of New South Wales, Australia." *Wetlands Ecology and Management* 7: 37–46. https://doi.org/10.1023/A:1008416925403.

Bruins, H., M. Evenari, and U. Nessler. 1986. "Rainwater Harvesting Agriculture for Food Production in Arid Zones: The Challenge of the African Famine." *Applied Geography* 6: 13–32. https://doi.org/10.1016/0143-6228(86)90026-3.

Brune, G. M. 1953. "Trap Efficiency of Reservoirs." *Eos, Transactions American Geophysical Union* 34: 407–418. https://doi.org/10.1029/TR034i003p00407.

Brykała, D., and Z. Podgórski. 2020. "Evolution of Landscapes Influenced by Watermills, Based on Examples From Northern Poland." *Landscape and Urban Planning* 198: 103798. https://doi.org/10.1016/j.landurbplan.2020.103798.

Buchty-Lemke, M., and F. Lehmkuhl. 2018. "Impact of Abandoned Water Mills on Central European Foothills to Lowland Rivers: A Reach Scale Example From the Wurm River, German." *Geografiska Annaler: Series A, Physical Geography* 100: 221–239. https://doi.org/10.1080/04353676.2018.1425621.

Burchsted, D., M. Daniels, R. Thorson, and J. Vokoun. 2010. "The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters." *Bioscience* 60: 908–922. https://doi.org/10.1525/bio.2010.60.11.7.

Burgin, A. J., and S. K. Hamilton. 2007. "Have We Overemphasized the Role of Denitrification in Aquatic Ecosystems? A Review of Nitrate Removal Pathways." *Frontiers in Ecology and the Environment* 5: 89–96.

Burns, D. A., and J. J. McDonnell. 1998. "Effects of a Beaver Pond on Runoff Processes: Comparison of Two Headwater Catchments." *Journal of Hydrology* 205: 248–264. https://doi.org/10.1016/S0022-1694(98)00081-X.

Bush, B. M., C. Stenert, L. Maltchik, and D. P. Batzer. 2019. "Beaver-Created Successional Gradients Increase β-Diversity of Invertebrates by Turnover in Stream-Wetland Complexes." *Freshwater Biology* 64: 1265–1274. https://doi.org/10.1111/fwb.13302.

Butler, D. R., and G. P. Malanson. 1995. "Sedimentation Rates and Patterns in Beaver Ponds in a Mountain Environment." *Geomorphology* 13: 255–269. https://doi.org/10.1016/0169-555X(95)00031-Y.

Butler, D. R., and G. P. Malanson. 2005. "The Geomorphic Influences of Beaver Dams and Failures of Beaver Dams." *Geomorphology* 71: 48–60. https://doi.org/10.1016/j.geomorph.2004.08.016.

Bylak, A., K. Kukula, and J. Mitka. 2014. "Beaver Impact on Stream Fish Life Histories: The Role of Landscape and Local Attributes." *Canadian Journal of Fisheries and Aquatic Sciences* 71: 1603–1615. https://doi.org/10.1139/cjfas-2014-0105.

Callow, J. N., and K. R. J. Smettem. 2009. "The Effect of Farm Dams and Constructed Banks on Hydrologic Connectivity and Runoff Estimation in Agricultural Landscapes." *Environmental Modelling & Software* 24: 959–968. https://www.sciencedirect.com/science/article/pii/S1364815209000358#sec5.

Canals, R. M., V. Ferrer, A. Iriarte, S. Carcamo, S. L. Emeterio, and E. Villanueva. 2011. "Emerging Conflicts for the Environmental Use of Water in High-Valuable Rangelands. Can Livestock Water Ponds Be Managed as Artificial Wetlands for Amphibians?" *Ecological Engineering* 37: 1443–1452. https://www.sciencedirect.com/science/article/pii/S0925857411000516.

Carey, C. C., J. P. Doubek, R. P. McClure, and P. C. Hanson. 2018. "Oxygen Dynamics Control the Burial of Organic Carbon in a Eutrophic Reservoir." *Limnology and Oceanography Letters* 3: 293–301. https://doi.org/10.1002/lol2.10057.

Castillo, V. M., W. M. Mosch, C. C. Garcia, G. G. Barbera, J. A. N. Cano, and F. Lopez-Bermudez. 2007. "Effectiveness and Geomorphological Impacts of Check Dams for Soil Erosion Control in a Semiarid Mediterranean Catchment: El Carcavo (Murcia, Spain)." *Catena* 70: 416–427. https://doi.org/10.1016/j.catena.2006.11.009.

Chang, H. Y., M. C. Chiu, Y. L. Chuang, et al. 2017. "Community Responses to Dam Removal in a Subtropical Mountainous Stream." *Aquatic Sciences* 79: 967–983. https://doi.org/10.1007/s00027-017-0545-0.

Chaplin, J. J., R. A. Brightbill, and M. D. Bilger. 2005. "Effects of Removing Good Hope Mill Dam on selected physical, chemical, and biological characteristics of Conodoguinet Creek, Cumberland County, Pennsylvania." U.S. Geological Survey Scientific Investigations Report 2005-5226. https://doi.org/10.3133/sir20055226.

Cheng, Y., P. Li, G. Xu, et al. 2018. "Factors That Influence Soil Total Phosphorus Sources on Dam Fields That Are Part of Ecological Construction Programs on the Loess Plateau, China." *Catena* 171: 107–114. https://doi.org/10.1016/j.catena.2018.07.006.

Chester, E. T., and B. J. Robson. 2013. "Anthropogenic Refuges for Freshwater Biodiversity: Their Ecological Characteristics and Management." *Biological Conservation* 166: 64–75. https://doi.org/10.1016/j.biocon.2013.06.016.

Chin, A., L. R. Laurencio, and A. E. Martinez. 2008. "The Hydrologic Importance of Small- and Medium-Sized Dams: Examples From Texas." *Professional Geographer* 60: 238–251. https://doi.org/10.1080/00330120701836261.

Churchill, M. A. 1948. "Discussion of Paper by L.C. Gottschalk 'Analyses and Use of Reservoir Sedimentation Data'." In *Federal Inter-Agency Sedimentation Conference Proceedings*, 139–140. US Geological Survey.

Clay, P., and C. R. Salisbury. 1990. "A Normal Mill Dam and Other Sites at Hemington Fields, Castle Donington, Leicestershire." *Archaeological Journal* 147: 276–307. https://doi.org/10.1080/00665983.1990.11077946.

Coles, B. 2000. "Beaver Territories: The Resource Potential for Humans." In *Human Ecodynamics*, edited by G. Bailey, R. Charles, and N. Winder, 80–89. Oxbow Books.

Collier, M., R. H. Webb, and J. C. Schmidt. 1996. *Dams and Rivers: A Primer on the Downstream Effects of Dams*. Vol. 1126. US Geological Survey Circular.

Comiti, F., L. Mao, A. Lenzi, and M. Siligardi. 2009. "Artificial Steps to Stabilize Mountain Rivers: A Post-Project Ecological Assessment." *River Research and Applications* 25: 639–659. https://doi.org/10.1002/rra.1234.

Conesa-García, C., F. Lopez-Bermudez, and R. Garcial-Lorenzo. 2007. "Bed Stability Variations After Check Dam Construction in Torrential Channels (South-East Spain)." *Earth Surface Processes and Landforms* 32: 2165–2184. https://doi.org/10.1002/esp.1521.

Corline, N. J., P. Vasquez-Housley, E. Yokel, C. Gilmore, B. Stapleton, and R. A. Lusardi. 2023. "When Humans Work Like Beavers: Riparian Restoration Enhances Invertebrate Gamma Diversity and Habitat Heterogeneity." *Restoration Ecology* 31: e13690. https://doi.org/10.1111/rec.13690.

Correll, D. L., T. E. Jordan, and D. E. Weller. 2000. "Beaver Pond Biogeochemical Effects in the Maryland Coastal Plain." *Biogeochemistry* 49: 217–239. https://doi.org/10.1023/A:1006330501887.

Culler, R. C. 1961. *Hydrology of the Upper Cheyenne River Basin: Part A. Hydrology of Stock-Water Reservoirs in Upper Cheyenne Basin*. US Geological Survey Water-Supply Paper 1531.

Cutting, K. A., J. M. Ferguson, M. L. Anderson, K. Cook, S. C. Davis, and R. Levine. 2018. "Linking Beaver Dam Affected Flow Dynamics to Upstream Passage of Arctic Grayling." *Ecology and Evolution* 8: 12905–12917. https://doi.org/10.1002/ece3.4728.

De Visscher, M., J. Nyssen, J. Pontzeele, P. Billi, and A. Frankl. 2014. "Spatio-Temporal Sedimentation Patterns in Beaver Ponds Along the Chevral River, Ardennes, Belgium." *Hydrological Processes* 28: 1602–1615. https://doi.org/10.1002/hyp.9702.

Djuma, H., A. Bruggeman, C. Camera, M. Eliades, and K. Kostarelos. 2017. "The Impact of a Check Dam on Groundwater Recharge and Sedimentation in an Ephemeral Stream." *Water* 9, no. 10: 813. https://doi.org/10.3390/w9100813.

do Prado, A. H., D. Mair, P. Garefalakis, et al. 2024. "Check Dam Impact on Sediment Loads: Example of the Guerbe River in the Swiss Alps – A Catchment Scale Experiment." *Hydrology and Earth System Sciences* 28: 1173–1190. https://doi.org/10.5194/hess-28-1173-2024.

Donovan, M., A. Miller, and M. Baker. 2016. "Reassessing the Role of Milldams in Piedmont Floodplain Development and Remobilization." *Geomorphology* 268: 133–145. https://doi.org/10.1016/j.geomorph.2016.06.007.

Doucette, T. M. 2009. "Local Fish Community Structure Before and After Breaching of the Woolen Mills Dam, Rivanna River, Virginia." MA thesis, University of Virginia.

Duesterhaus, J. L., J. M. Ham, C. E. Owensby, and J. T. Murphy. 2008. "Water Balance of a Stock-Watering Pond in the Flint Hills of Kansas." *Rangeland Ecology & Management* 61: 329–338. https://doi.org/10.2111/07-097.1.

Dunn, S. B., S. L. Rathburn, and E. Wohl. 2024. "Post-Fire Sediment Attenuation in Beaver Ponds, Rocky Mountains, CO and WY, USA." *Earth Surface Processes and Landforms* 49: 4340–4354. https://doi.org/10.1002/esp.5970.

Ecke, F., O. Levanoni, J. Audet, et al. 2017. "Meta-Analysis of Environmental Effects of Beaver in Relation to Artificial Dams." *Environmental Research Letters* 12: 113002.

Fajer, M., and M. A. Rzetala. 2017. "Mill Pond Sediments as the Indicator of the Environment of the Drainage Area (an Example of the Liswarta River, Odra Basin, Poland)." *Environmental Science and Pollution Research* 25: 5832–5847. https://doi.org/10.1007/s11356-017-0909-y.

Fedyń, I., W. Sobociński, S. Czyzowicz, J. Wyka, and M. Ciach. 2024. "Ecosystem Engineers Cause Biodiversity Spill-Over: Beavers Are Associated With Breeding Bird Assemblages on Both Wetlands and Adjacent Terrestrial Habitats." *Science of the Total Environment* 950: 175166. https://doi.org/10.1016/j.scitotenv.2024.175166.

Fenci, J. S., M. E. Mather, K. H. Costigan, and M. D. Daniels. 2015. "How Big of an Effect Do Small Dams Have? Using Geomorphological Footprints to Quantify Spatial Impact of Low-Head Dams and Identify Patterns of Across-Dam Variation." *PLoS One* 10: e0141210. https://doi.org/10.1371/journal.pone.0141210.

Florsheim, J. L., A. Chin, and A. Nichols. 2013. "Effects of Multiple Small Stock-Pond Dams in a Coastal Watershed in Central California: Implications for Removing Small Dams for Restoration." In *The Challenges of Dam Removal and River Restoration*, edited by J. V. De Graff and J. E. Evans. GSA Reviews in Engineering Geology, Geological Society of America. https://doi.org/10.1130/2013.4121(12).

Follett, E., K. Beven, B. Hankin, D. Mindham, and N. Chappell. 2024. "The Importance of Retention Times in Natural Flood Management Interventions." *Proceedings of IAHS* 382: 197–201. https://doi.org/10.5194/piahs-385-197-2024.

Frankl, A., J. Nyssen, M. Vanmaercke, and J. Poesen. 2021. "Gully Prevention and Control: Techniques, Failures and Effectiveness." *Earth Surface Processes and Landforms* 46: 220–238. https://doi.org/10.1002/esp.5033.

Froneman, A., M. J. Mangnall, R. M. Little, and T. M. Crowe. 2001. "Waterbird Assemblages and Associated Habitat Characteristics of Farm Ponds in the Western Cape, South Africa." *Biodiversity and Conservation* 10: 251–270. https://doi.org/10.1023/A:1008904421948.

Galia, T., V. Skarpich, and S. Ruman. 2021. "Impact of Check Dam Series on Coarse Sediment Connectivity." *Geomorphology* 377: 107595. https://doi.org/10.1016/j.geomorph.2021.107595.

Gangloff, M. M. 2013. "Taxonomic and Ecological Tradeoffs Associated With Small Dam Removals." *Aquatic Conservation: Marine and Freshwater Ecosystems* 23: 475–480. https://doi.org/10.1002/aqc.2383.

Gatti, R. C., T. V. Callaghan, I. Rozhkova-Timina, et al. 2018. "The Role of Eurasian Beaver (*Castor fiber*) in the Storage, Emission and Deposition of Carbon in Lakes and Rivers of the River Ob Flood Plain, Western Siberia." *Science of the Total Environment* 644: 1271–1379. https://doi.org/10.1016/j.scitotenv.2018.07.042.

Gibson, P. P., J. D. Olden, and M. W. O'Neill. 2015. "Beaver Dams Shift Desert Fish Assemblages Toward Dominance by Non-native Species (Verde River, Arizona, USA)." *Ecology of Freshwater Fish* 24: 355–372. https://doi.org/10.1111/eff.12150.

Giles, M., N. Morley, E. M. Baggs, and T. J. Daniel. 2012. "Soil Nitrate Reducing Processes – Drivers, Mechanisms for Spatial Variation, and Significance for Nitrous Oxide Production." *Frontiers in Microbiology* 3: 407. https://doi.org/10.3389/fmicb.2012.00407.

González-Romero, J., M. E. Lucas-Borja, P. A. Plaza-Alvarez, J. Sagra, D. Moya, and J. De Las Heras. 2019. "Short-Term Effects of Postfire Check-Dam Construction on Ephemeral Stream Vegetation in a Semiarid Climate of SE Spain." *Science of the Total Environment* 671: 776–785. https://doi.org/10.1016/j.scitotenv.2019.03.366.

Graeb, B. D. S., D. W. Willis, and B. D. Spindler. 2009. "Shifts in Sauger Spawning Locations After 40 Years of Reservoir Ageing: Influence of a Novel Delta Ecosystem in the Missouri River, USA." *River Research and Applications* 25: 153–159. https://doi.org/10.1002/rra.1107.

Graham, C., and A. E. Goodenough. 2024. "Beneficial Impacts of Eurasian Beaver (*Castor fiber*) Reintroduction on Bat Communities and Aquatic Macroinvertebrate Prey: A Case Study From Lowland Britain." *Acta Chiropterologica* 26: 63–76. https://doi.org/10.3161/15081109ACC2024.26.1.006.

Grill, G., B. Lehner, A. E. Lumsden, G. K. MacDonald, C. Zarfl, and C. R. Liermann. 2015. "An Index-Based Framework for Assessing Patterns and Trends in River Fragmentation and Flow Regulation by Global Dams at Multiple Scales." *Environmental Research Letters* 10, no. 1: 015001. https://doi.org/10.1088/1748-9326/10/1/015001.

Grudzinski, B. P., H. Cummins, and T. K. Vang. 2020. "Beaver Canals and Their Environmental Effects." *Progress in Physical Geography: Earth and Environment* 44: 189–211. https://doi.org/10.1177/0309133319873116.

Grudzinski, B. P., K. Fritz, H. E. Golden, et al. 2022. "A Global Review of Beaver Dam Impacts: Stream Conservation Implications Across Biomes." *Global Ecology and Conservation* 37: e02163. https://doi.org/10.1016/j.gecco.2022.e02163.

Hale, J. R., M. C. Mims, M. T. Bogan, and J. D. Olden. 2015. "Links Between Two Interacting Factors, Novel Habitats and Non-native Predators, and Aquatic Invertebrate Communities in a Dryland Environment." *Hydrobiologia* 746: 313–326. https://doi.org/10.1007/s10750-014-2024-0.

Hall, C. J., A. Jordaan, and M. G. Frisk. 2011. "The Historic Influence of Dams on Diadromous Fish Habitat With a Focus on River Herring and Hydrologic Longitudinal Connectivity." *Landscape Ecology* 26: 95–107. https://doi.org/10.1007/s10980-010-9539-1.

Halley, D. J., A. P. Saveljev, and F. Rosell. 2021. "Population and Distribution of Beavers *Castor fiber* and *Castor canadensis* in Eurasia." *Mammal Review* 51: 1–24. https://doi.org/10.1111/mam.12216.

Hart, J. F. 2004. "Fish, Dams, and James Madison: Eighteenth-Century Species Protection and the Original Understanding of the Takings Clause." *Maryland Law Review* 63: 287–319.

Hartman, B. D., B. Bookhagen, and O. A. Chadwick. 2016. "The Effect of Check Dams and Other Erosion Control Structures on the Restoration of Andean Bofedal Ecosystems." *Restoration Ecology* 24: 761–772. https://doi.org/10.1111/rec.12402.

Hazell, D., J. M. Hero, D. Lindenmayer, and R. Cunningham. 2004. "A Comparison of Constructed and Natural Habitat for Frog Conservation in an Australian Agricultural Landscape." *Biological Conservation* 119: 61–71. https://doi.org/10.1016/j.biocon.2003.10.022.

Heller, J. A. 1999. "The Effects of Stock Ponds on Downstream Potential Recharge in the Arivaca Creek Watershed." MS thesis, University of Arizona. https://repository.arizona.edu/handle/10150/191310.

Hill, B., Q. Liang, L. Bosher, H. Chen, and A. Nicholson. 2023. "A Systematic Review of Natural Flood Management Modelling: Approaches, Limitations, and Potential Solutions." *Journal of Flood Risk Management* 16: e12899. https://doi.org/10.1111/jfr3.12899.

Hill, M. J., J. Biggs, I. Thornhill, et al. 2017. "Urban Ponds as an Aquatic Biodiversity Resource in Modified Landscapes." *Global Change Biology* 23: 986–999. https://doi.org/10.1111/gcb.13401.

Hinshaw, S., and E. Wohl. 2023. "Carbon Sequestration Potential of Process-Based River Restoration." *River Research and Applications* 39: 1812–1827. https://doi.org/10.1002/rra.4183.

Hoch, R. A. 2012. "Beaver and Mill Dams Alter Freshwater Mussel Habitat, Growth, and Survival in North Carolina Piedmont Streams." MS thesis, Appalachian State University.

Hogg, R. S., S. M. Coghlan, J. Zydlewski, and C. Gardner. 2015. "Fish Community Response to a Small-Stream Dam Removal in a Maine Coastal River Tributary." *Transactions of the American Fisheries Society* 144: 467–479. https://doi.org/10.1080/00028487.2015.1007164.

Hood, G. A., and D. G. Larson. 2014. "Beaver-Created Habitat Heterogeneity Influences Aquatic Invertebrate Assemblages in Boreal Canada." *Wetlands* 34: 19–29. https://doi.org/10.1007/s13157-013-0476-z.

Hooker, J., T. Foxley, E. L. Stone, and P. R. Lintott. 2024. "Re-Establishing Historic Ecosystem Links Through Targeted Species Reintroduction: Beaver-Mediated Wetlands Support Increased Bat Activity." *Science of the Total Environment* 951: 175661. https://doi.org/10.1016/j.scitotenv.2024.175661.

Hossack, B. R., W. R. Gould, D. A. Patla, et al. 2015. "Trends in Rocky Mountain Amphibians and the Role of Beaver as a Keystone Species." *Biological Conservation* 187: 260–269. https://doi.org/10.1016/j.biocon.2015.05.005.

Huzita, T., R. Noda, and C. Kayo. 2020. "Regional Economic Impacts From Timber Check Dam Construction – A Comparison With Concrete Check Dam Construction." *Forests* 11, no. 10: 1073. https://doi.org/10.3390/f11101073.

Inamdar, S., E. K. Peck, M. Peipoch, et al. 2022. "Saturated, Suffocated, and Salty: Human Legacies Produce Hot Spots of Nitrogen in Riparian Zones." *Journal of Geophysical Research: Biogeosciences* 127, no. 12: e2022JG007138. https://doi.org/10.1029/2022JG007138.

Inamdar, S., M. Peipoch, A. J. Gold, et al. 2021. "Ghosts of Landuse Past: Legacy Effects of Milldams for Riparian Nitrogen (N) Processing and Water Quality Functions." *Environmental Research Letters* 16: 035016. https://doi.org/10.1088/1748-9326/abd9f5.

Inamdar, S., M. Peipoch, M. Sena, et al. 2024. "Riparian Groundwater Nitrogen (N) Isotopes Reveal Human Imprints of Dams and Road Salt Salinization." *Geophysical Research Letters* 51, no. 5: e2023GL106888. https://doi.org/10.1029/2023GL106888.

Inamdar, S., N. Sienkiewicz, A. Lutgen, G. Jiang, and J. Kan. 2020. "Streambank Legacy Sediments in Surface Waters: Phosphorus Sources or Sinks?" *Soil Systems* 4, no. 2: 30. https://doi.org/10.3390/soilsystems4020030.

Iskin, E. P., and E. Wohl. 2023. "Beyond the Case Study: Characterizing Natural Floodplain Heterogeneity in the United States." *Water Resources Research* 59, no. 8: e2023WR035162. https://doi.org/10.1029/2023WR035162.

Ives, R. L. 1942. "The Beaver-Meadow Complex." *Journal of Geomorphology* 5: 191–203.

James, W. F., W. B. Richardson, and D. M. Soballe. 2008. "Effects of Residence Time on Summer Nitrate Uptake in Mississippi River Flow-Regulated Backwaters." *River Research and Applications* 24: 1206–1217. https://doi.org/10.1002/rra.1150.

Jansson, R., C. Nilsson, and B. Renofalt. 2000. "Fragmentation of Riparian Floras in Rivers With Multiple Dams." *Ecology* 81: 899–903. https://doi.org/10.1890/0012-9658(2000)081[0899:FORFIR]2.0.CO;2.

Janzen, K., and C. J. Westbrook. 2011. "Hyporheic Flows Along a Channelled Peatland: Influence of Beaver Dams." *Canadian Water Resources Journal* 36: 331–347. https://doi.org/10.4296/cwrj3604846.

John, S., and A. Klein. 2004. "Hydrogeomorphic Effects of Beaver Dams on Floodplain Morphology: Avulsion Processes and Sediment Fluxes in Upland Valley Floors (Spessart, Germany)." *Quaternaire* 15: 219–231.

Johnson, B. G., H. Rieden, and R. P. Mullinax. 2023. "Legacy Sediment and Stream Incision in the North Carolina Piedmont: Fluvial Evolution Before and After Mill Dam Construction." *Anthropocene* 44: 100405. https://doi.org/10.1016/j.ancene.2023.100405.

Johnson, M. F., C. R. Thorne, J. M. Castro, et al. 2020. "Biomic River Restoration: A New Focus for River Management." *River Research and Applications* 36: 3–12. https://doi.org/10.1002/rra.3529.

Johnston, C. A. 2014. "Beaver Pond Effects on Carbon Storage in Soils." *Catena* 213: 371–378. https://doi.org/10.1016/j.geoderma.2013.08.025.

Johnston, C. A. 2015. "Fate of 150 Year Old Beaver Ponds in the Laurentian Great Lakes Region." *Wetlands* 35: 1013–1019. https://link.springer.com/article/10.1007/s13157-015-0688-5.

Johnston, C. A. 2017. *Beavers: Boreal Ecosystem Engineers*. Springer. https://doi.org/10.1007/978-3-319-61533-2_8.

Jordan, C. E., and E. Fairfax. 2022. "Beaver: The North American Freshwater Climate Action Plan." *Wiley Interdisciplinary Reviews Water* 9: e1592. https://doi.org/10.1002/wat2.1592.

Joshi, B., E. Bacmeister, E. Peck, M. Peipoch, J. Kan, and S. Inamdar. 2023. "Sediment-Nitrogen (N) Connectivity: Suspended Sediments in Streams as N Exporters and Reactors for Denitrification and Assimilatory N Uptake During Storms." *Frontiers in Water* 5: 1254225. https://doi.org/10.3389/frwa.2023.1254225.

Kaiser, K., N. Keller, A. Brande, et al. 2018. "A Large-Scale Medieval Dam-Lake Cascade in Central Europe: Water Level Dynamics of the Havel River, Berlin-Brandenburg Region, Germany." *Geoarchaeology* 33: 237–259. https://doi.org/10.1002/gea.21649.

Kanehl, P. D., J. Lyons, and J. E. Nelson. 1997. "Changes in the Habitat and Fish Community of the Milwaukee River, Wisconsin, Following Removal of the Woolen Mills Dam." *North American Journal of Fisheries Management* 17: 387–400. https://doi.org/10.1577/1548-8675(1997)017%3C0387:CITHAF%3E2.3.CO;2.

Kemp, P. S., T. A. Worthington, T. E. L. Langford, A. R. J. Tree, and M. J. Gaywood. 2012. "Qualitative and Quantitative Effects of Reintroduced Beavers on Stream Fish." *Fish and Fisheries* 13: 158–181. https://doi.org/10.1111/j.1467-2979.2011.00421.x.

Klotz, R. L. 1998. "Influence of Beaver Ponds on the Phosphorus Concentration of Stream Water." *Canadian Journal of Fisheries and Aquatic Sciences* 55: 1228–1235. https://doi.org/10.1139/f97-318.

Klotz, R. L. 2010. "Reduction of High Nitrate Concentrations in a Central New York State Stream Impounded by Beaver." *Northeastern Naturalist* 17: 349–356. https://doi.org/10.1656/045.017.0301.

Kondolf, G. M., H. Piegay, and N. Landon. 2002. "Channel Response to Increased and Decreased Bedload Supply From Land Use Change: Contrasts Between Two Catchments." *Geomorphology* 45: 35–51. https://doi.org/10.1016/S0169-555X(01)00188-X.

Kramer, N., E. E. Wohl, and D. L. Harry. 2012. "Using Ground Penetrating Radar to 'Unearth' Buried Beaver Dams." *Geology* 40: 43–46. https://pubs.geoscienceworld.org/gsa/geology/article-abstract/40/1/43/130695/Using-ground-penetrating-radar-to-unearth-buried.

Kreiling, R. M., W. B. Richardson, J. C. Cavanaugh, and L. A. Bartsch. 2011. "Summer Nitrate Uptake and Denitrification in an Upper Mississippi River Backwater Lake: The Role of Uprooted Aquatic Vegetation." *Biogeochemistry* 104: 309–324. https://doi.org/10.1007/s10533-010-9503-9.

Lane, L. J., M. Hernandez, and M. Nichols. 1997. "Processes Controlling Sediment Yield From Watersheds as Functions of Spatial Scale." *Environmental Modelling & Software* 12: 355–369. https://doi.org/10.1016/S1364-8152(97)00027-3.

Larsen, A., J. R. Larsen, and S. N. Lane. 2021. "Dam Builders and Their Works: Beaver Influences on the Structure and Function of River Corridor Hydrology, Geomorphology, Biogeochemistry and Ecosystems." *Earth-Science Reviews* 218: 103623. https://doi.org/10.1016/j.earscirev.2021.103623.

Laurel, D., and E. Wohl. 2019. "The Persistence of Beaver-Induced Geomorphic Heterogeneity and Organic Carbon Stock in River Corridors." *Earth Surface Processes and Landforms* 44: 342–353. https://doi.org/10.1002/esp.4486.

Lautz, L., C. Kelleher, P. Vidon, J. Coffman, C. Riginos, and H. Copeland. 2019. "Restoring Stream Ecosystem Function With Beaver Dam Analogues: Let's Not Make the Same Mistake Twice." *Hydrological Processes* 33: 174–177. https://doi.org/10.1002/hyp.13333.

Lautz, L. K., D. I. Siegel, and R. L. Bauer. 2006. "Impact of Debris Dams on Hyporheic Interaction Along a Semi-Arid Stream." *Hydrological Processes* 20: 183–196. https://doi.org/10.1002/Hyp.5910.

Law, A., F. McLean, and N. J. Willby. 2016. "Habitat Engineering by Beaver Benefits Aquatic Biodiversity and Ecosystem Processes in Agricultural Streams." *Freshwater Biology* 61: 486–499. https://doi.org/10.1111/FWB.12721.

Lazar, J. G., K. Addy, A. J. Gold, P. M. Groffman, R. A. McKinney, and D. Q. Kellogg. 2015. "Beaver Ponds: Resurgent Nitrogen Sinks for Rural Watersheds in the Northeastern United States." *Journal of Environmental Quality* 44: 1684–1693. https://doi.org/10.2134/jeq2014.12.0540.

Lazar, J. G., K. Addy, M. K. Welsh, A. J. Gold, and P. M. Groffman. 2014. "Resurgent Beaver Ponds in the Northeastern United States: Implications for Greenhouse Gas Emissions." *Journal of Environmental Quality* 43: 1844–1852. https://doi.org/10.2134/jeq2014.02.0065.

Ledford, S. H., S. Miller, L. Pangle, and E. B. Sudduth. 2023. "Hyporheic Exchange in an Urban Beaver Pond Mediates High Nutrient Groundwater Inflow and Pond Productivity." *Journal of Hydrology* 622B: 129758. https://doi.org/10.1016/j.jhydrol.2023.129758.

Lewis, E., S. Inamdar, A. J. Gold, et al. 2021. "Draining the Landscape: How Do Nitrogen Concentrations in Riparian Groundwater and Stream Water Change Following Milldam Removal?" *Journal of Geophysical Research: Biogeosciences* 126, no. 8: e2021JG006444. https://doi.org/10.1029/2021JG006444.

Lewis, S. E., Z. T. Bainbridge, P. M. Kuhnert, et al. 2013. "Calculating Sediment Trapping Efficiencies for Reservoirs in Tropical Settings: A Case Study From the Burdekin Falls Dam, NE Australia." *Water Resources Research* 49: 1017–1029. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/wrcr.20117.

Li, J., S. Dong, S. Liu, Z. Yang, M. Peng, and C. Zhao. 2013. "Effects of Cascading Hydropower Dams on the Composition, Biomass and Biological Integrity of Phytoplankton Assemblages in the Middle Lancang-Mekong River." *Ecological Engineering* 60: 316–324. https://www.sciencedirect.com/science/article/pii/S0925857413002802.

Liermann, C. R., C. Nilsson, J. Robertson, and R. Y. Ng. 2012. "Implications of Dam Obstruction for Global Freshwater Fish Diversity." *Bioscience* 62: 539–548. https://academic.oup.com/bioscience/article/62/6/539/249111.

Liu, C., Z. Li, Y. Dong, et al. 2017. "Do Land Use Change and Check-Dam Construction Affect a Real Estimate of Soil Carbon and Nitrogen Stocks on the Loess Plateau of China?" *Ecological Engineering* 101: 220–226. https://doi.org/10.1016/j.ecoleng.2017.01.036.

Liu, Y., W. Yang, Z. Yu, et al. 2014. "Assessing Effects of Small Dams on Stream Flow and Water Quality in an Agricultural Watershed." *Journal of Hydrologic Engineering* 19, no. 10: 05014015. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001005.

Livermore, J., M. Trainor, and M. S. Bednarski. 2017. "Successful Spawning of Anadromous *Petromyzon marinus* L. (Sea Lamprey) in a Restored Stream Channel Following Dam Removal." *Northeastern Naturalist* 24: 380–390. https://doi.org/10.1656/045.024.0306.

Lokteff, R. L., B. B. Roper, and J. M. Wheaton. 2013. "Do Beaver Dams Impede the Movement of Trout?" *Transactions of the American Fisheries Society* 142: 1114–1125. https://doi.org/10.1080/00028487.2013.797497.

Lowdermilk, W. C. 1960. "The Reclamation of a Man-Made Desert." *Scientific American* 202: 54–63.

Lowrance, R., L. S. Altier, J. D. Newbold, et al. 1997. "Water Quality Functions of Riparian Forest Buffers in Chesapeake Bay Watersheds." *Environmental Management* 21: 687–712. https://doi.org/10.1007/s002679900060.

Lü, Y., R. Sun, B. Fu, and Y. Wang. 2012. "Carbon Retention by Check Dams: Regional Scale Estimation." *Ecological Engineering* 44: 139–146. https://doi.org/10.1016/j.ecoleng.2012.03.020.

Lucas-Borja, M. E., G. Piton, Y. Yu, C. Castillo, and D. A. Zema. 2021. "Check Dams Worldwide: Objectives, Functions, Effectiveness and Undesired Effects." *Catena* 204: 105390. https://doi.org/10.1016/j.catena.2021.105390.

Lucas-Borja, M. E., D. A. Zema, M. D. H. Guzman, et al. 2018. "Exploring the Influence of Vegetation Cover, Sediment Storage Capacity and Channel Dimensions on Stone Check Dam Conditions and Effectiveness in a Large Regulated River in Mexico." *Ecological Engineering* 122: 39–47. https://doi.org/10.1016/j.ecoleng.2018.07.025.

Luzzadder-Beach, S., T. P. Beach, and N. P. Dunning. 2012. "Wetland Fields as Mirrors of Drought and the Maya Abandonment." *Proceedings of the National Academy of Science* 109: 3646–3651. https://doi.org/10.1073/pnas.1114919109.

Lyons, N. J., M. J. Starek, K. W. Wegmann, and H. Mitasova. 2015. "Bank Erosion of Legacy Sediment at the Transition From Vertical to Lateral Stream Incision." *Earth Surface Processes and Landforms* 40: 1764–1778. https://doi.org/10.1002/esp.3753.

Maaß, A. L., and H. Schüttrumpf. 2019. "Elevated Floodplains and Net Channel Incision as a Result of the Construction and Removal of Water Mills." *Geografiska Annaler: Series A, Physical Geography* 101: 157–176. https://doi.org/10.1080/04353676.2019.1574209.

Maavara, T., R. Lauerwald, P. Regnier, and P. Van Cappellen. 2017. "Global Perturbation of Organic Carbon Cycling by River Damming." *Nature Communications* 8: 15347. https://www.nature.com/articles/ncomms15347.

MacDonald, D. W., F. H. Tattersall, E. D. Brown, and D. Balharry. 1995. "Reintroducing the European Beaver to Britain: Nostalgic Meddling or Restoring Biodiversity?" *Mammal Review* 25: 161–200. https://doi.org/10.1111/j.1365-2907.1995.tb00443.x.

Macfarlane, W. W., J. M. Wheaton, N. Bouwes, et al. 2017. "Modeling the Capacity of Riverscapes to Support Beaver Dams." *Geomorphology* 277: 72–99. https://doi.org/10.1016/j.geomorph.2015.11.019.

Magilligan, F. J., K. H. Nislow, B. E. Kynard, and A. M. Hackman. 2016. "Immediate Changes in Stream Channel Geomorphology, Aquatic Habitat, and Fish Assemblages Following Dam Removal in a Small Upland Catchment." *Geomorphology* 252: 158–170. https://doi.org/10.1016/j.geomorph.2015.07.027.

Maret, T. J., M. Parker, and T. E. Fannin. 1987. "The Effect of Beaver Ponds on the Nonpoint Source Water Quality of a Stream in Southwestern Wyoming." *Water Research* 21: 263–268. https://doi.org/10.1016/0043-1354(87)90204-1.

Markwell, K. A., and C. S. Fellows. 2008. "Habitat and Biodiversity of On-Farm Water Storages: A Case Study in Southeast Queensland, Australia." *Environmental Management* 41: 234–249. https://doi.org/10.1007/s00267-007-9037-7.

May, S. M., D. E. Naugle, and K. F. Higgins. 2002. "Effects of Nongame Wetland Birds in Western South Dakota Stock Ponds, USA." *Waterbirds* 25: 51–55. https://www.jstor.org/stable/1522451.

Mbaka, J. G., and M. W. Mwaniki. 2017. "A Critical Review of the Effect of Water Storage Reservoirs on Organic Matter Decomposition in Rivers." *Environmental Reviews* 25: 193–198. https://doi.org/10.1139/er-2016-0041.

Mendonça, R., N. Barros, L. O. Vidal, F. Pacheco, S. Kosten, and F. Roland. 2012. "Greenhouse Gas Emissions From Hydroelectric Reservoirs: What Knowledge Do We Have & What Is Lacking?" In *Greenhouse Gases: Emission, Measurement and Management*, edited by G. Liu, 55–78. Intech Open.

Mendonça, R., R. A. Muller, D. Clow, et al. 2017. "Organic Carbon Burial in Global Lakes and Reservoirs." *Nature Communications* 8: 1694. https://www.nature.com/articles/s41467-017-01789-6.

Merritts, D., R. Walter, M. Rahnis, et al. 2013. "The Rise and Fall of Mid-Atlantic Streams: Millpond Sedimentation, Milldam Breaching, Channel Incision, and Stream Bank Erosion." In *The Challenges of Dam Removal and River Restoration*, edited by J. V. De Graff and J. E. Evans. GSA Reviews in Engineering Geology, Geological Society of America. https://doi.org/10.1130/2013.4121(14).

Merritts, D., R. Walter, M. Rahnis, et al. 2011. "Anthropocene Streams and Base-Level Controls From Historic Dams in the Unglaciated Mid-Atlantic Region, USA." *Philosophical Transactions of the Royal Society* 369: 976–1009.

Milliman, J. D. 1993. "Blessed Dams or Damned Dams?" *Nature* 386: 325–327. https://doi.org/10.1038/386325a0.

Mills, E. A. 1913. *In Beaver World*. University of Nebraska Press.

Mims, M. C., J. C. Drake, J. J. Lawler, and J. D. Olden. 2023. "Simulating the Response of a Threatened Amphibian to Climate-Induced Reductions in Breeding Habitat." *Landscape Ecology* 38: 1051–1068. https://doi.org/10.1007/s10980-023-01599-w.

Mims, M. C., C. E. Moore, and E. J. Shadle. 2020. "Threats to Aquatic Taxa in an Arid Landscape: Knowledge Gaps and Areas of Understanding for Amphibians of the American Southwest." *Wiley Interdisciplinary Reviews Water* 7: e1449. https://doi.org/10.1002/wat2.1449.

Mongil-Manso, J., V. Diaz-Guiterrez, J. Navarro-Hevia, M. Espina, and L. San Segundo. 2019. "The Role of Check Dams in Retaining Organic Carbon and Nutrients. A Study Case in the Sierra de Avila Mountain Range (Central Spain)." *Science of the Total Environment* 657: 1030–1040. https://doi.org/10.1016/j.scitotenv.2018.12.087.

Morgan, L. H. 1868. *The American Beaver and His Works*. J.B. Lippincott & Co.

Munir, T. M., and C. J. Westbrook. 2021. "Beaver Dam Analogue Configurations Influence Stream and Riparian Water Table Dynamics of a Degraded Spring-Fed Creek in the Canadian Rockies." *River Research and Applications* 37: 330–342. https://doi.org/10.1002/rra.3753.

Murray, D., B. T. Neilson, and J. Brahney. 2023. "Beaver Pond Geomorphology Influences Pond Nitrogen Retention and Denitrification." *Journal of Geophysical Research: Biogeosciences* 128, no. 4: e2022JG007199. https://doi.org/10.1029/2022JG007199.

Nagayama, S., N. Ishiyama, T. Seno, et al. 2020. "Time Series Changes in Fish Assemblages and Habitat Structures Caused by Partial Check Dam Removal." *Water* 12: 3357. https://doi.org/10.3390/w12123357.

Naiman, R. J., C. A. Johnston, and J. C. Kelley. 1988. "Alteration of North American Streams by Beaver." *Bioscience* 38: 753–762. https://doi.org/10.2307/1310784.

Naiman, R. J., and J. M. Melillo. 1984. "Nitrogen Budget of a Subarctic Stream Altered by Beaver (*Castor canadensis*)." *Oecologia* 62: 150–155. https://doi.org/10.1007/BF00379007.

Neace, H. 2023. "Water Quality and Soil Health Response to Beaver Dam Analogs in an Intermittent Stream in Southern Idaho." MS thesis, University of Idaho. https://www.proquest.com/openview/ba6ca37f8a0a2c9044f73af82d681323/1?pq-origsite=gscholar&cbl=18750&diss=y.

Nichols, M. H. 2006. "Measured Sediment Yield Rates From Semiarid Rangeland Watersheds." *Rangeland Ecology & Management* 59: 55–62. https://doi.org/10.2111/05-075R1.1.

Nichols, M. H., C. Magirl, N. F. Sayre, and J. R. Shaw. 2018. "The Geomorphic Legacy of Water and Erosion Control Structures in a Semiarid Rangeland Watershed." *Earth Surface Processes and Landforms* 43: 909–918. https://doi.org/10.1002/esp.4287.

Norbury, M., D. Shaw, and P. Jones. 2018. "Combining Hydraulic Modelling With Partnership Working: Towards Practical Natural Flood Management." *Engineering Sustainability* 172: 372–384. https://doi.org/10.1680/jensu.17.00025.

Nummi, P., W. Liao, O. Huet, E. Scarpulla, and J. Sundell. 2019. "The Beaver Facilitates Species Richness and Abundance of Terrestrial and Semi-Aquatic Mammals." *Global Ecology and Conservation* 20: e00701. https://doi.org/10.1016/j.gecco.2019.e00701.

Nummi, P., W. Liao, J. van der Schoor, and J. Loehr. 2021. "Beaver Creates Early Successional Hotspots for Water Beetles." *Biodiversity*

and Conservation 30: 2655–2670. https://doi.org/10.1007/s10531-021-02213-8.

Nummi, P., M. Vehkaoja, J. Pumpanen, and A. Ojala. 2018. "Beavers Affect Carbon Biogeochemistry: Both Short-Term and Long-Term Processes Are Involved." *Mammal Review* 48: 298–311. https://doi.org/10.1111/mam.12134.

Oertli, B., and K. M. Parris. 2019. "Review: Toward Management of Urban Ponds for Freshwater Biodiversity." *Ecosphere* 10: e02810. https://doi.org/10.1002/ecs2.2810.

Orazi, V., J. Hagge, M. M. Gossner, J. Muller, and M. Heurich. 2022. "A Biodiversity Boost From the Eurasian Beaver (*Castor fiber*) in Germany's Oldest National Park." *Frontiers in Ecology and Evolution* 10: 873307. https://doi.org/10.3389/fevo.2022.873307.

Pan, W., J. Kan, S. Inamdar, C. Chen, and D. Sparks. 2016. "Dissimilatory Microbial Iron Reduction Release DOC (Dissolved Organic Carbon) From Carbon-Ferrihydrite Association." *Soil Biology and Biochemistry* 103: 232–240. https://doi.org/10.1016/j.soilbio.2016.08.026.

Pearce, C., P. Vidon, L. Lautz, C. Kelleher, and J. Davis. 2021. "Impact of Beaver Dam Analogues on Hydrology in a Semi-Arid Floodplain." *Hydrological Processes* 35: e14275. https://doi.org/10.1002/hyp.14275.

Pearson, A. J., J. E. Pizzuto, and R. Vargas. 2016. "Influence of Run of River Dams on Floodplain Sediments and Carbon Dynamics." *Geoderma* 272: 51–63. https://doi.org/10.1016/j.geoderma.2016.02.029.

Peck, E. K., S. Inamdar, M. Sherman, et al. 2022. "Nitrogen Sinks or Sources? Denitrification and Nitrogen Removal Potential in Riparian Legacy Sediment Terraces Affected by Milldams." *Journal of Geophysical Research: Biogeosciences* 127: e2022JG007004. https://doi.org/10.1029/2022JG007004.

Peck, E. K., S. P. Inamdar, M. Peipoch, and A. J. Gold. 2023. "Influence of Relict Milldams on Riparian Sediment Biogeochemistry." *Journal of Soils and Sediments* 23: 2584–2599. https://doi.org/10.1007/s11368-023-03507-w.

Peeters, F., J. E. Fernandez, and H. Hofmann. 2019. "Sediment Fluxes Rather Than Oxic Methanogenesis Explain Diffusive CH_4 Emissions From Lakes and Reservoirs." *Scientific Reports* 9: 243. https://www.nature.com/articles/s41598-018-36530-w.

Peltzer, P. M., R. C. Lajmanovich, A. M. Attademo, and A. H. Beltzer. 2006. "Diversity of Anurans Across Agricultural Ponds in Argentina." In *Marine, Freshwater, and Wetlands Biodiversity*, edited by D. L. Hawksworth and A. T. Bull, 131–145. Springer. https://doi.org/10.1007/978-1-4020-5734-2_10.

Pfaff, P. J., K. J. Hase, and K. B. Gido. 2023. "Community Assembly of Prairie Farm Ponds: Build It and They Will Come, Stock It and They won't." *Canadian Journal of Fisheries and Aquatic Sciences* 80: 287–297. https://doi.org/10.1139/cjfas-2022-0075.

Phyoe, W. W., and F. Wang. 2019. "A Review of Carbon Sink or Source Effect on Artificial Reservoirs." *International journal of Environmental Science and Technology* 16: 2161–2174. https://doi.org/10.1007/s13762-019-02237-2.

Piton, G., S. Carladous, A. Recking, et al. 2017. "Why Do We Build Check Dams in Alpine Streams? An Historical Perspective From the French Experience." *Earth Surface Processes and Landforms* 42: 91–108. https://doi.org/10.1002/esp.3967.

Pizzuto, J., and M. O'Neal. 2009. "Increased Mid-Twentieth Century Riverbank Erosion Rates Related to the Demise of Mill Dams, South River, Virginia." *Geology* 37: 19–22. https://doi.org/10.1130/G25207A.1.

Podgórski, Z., and D. Szatten. 2020. "Changes in the Dynamics and Nature of Sedimentation in Mill Ponds as an Indicator of Environmental Changes in a Selected Lake Catchment (Chelminskie Lake District, Poland)." *Water* 12: 268. https://doi.org/10.3390/w12010268.

Poff, N. L., and D. D. Hart. 2002. "How Dams Vary and Why It Matters for the Emerging Science of Dam Removal." *Bioscience* 52, no. 8: 659–668. https://academic.oup.com/bioscience/article/52/8/659/254886.

Poff, N. L., J. D. Olden, D. M. Merritt, and D. M. Pepin. 2007. "Homogenization of Regional River Dynamics by Dams and Global Biodiversity Implications." *Proceedings of the National Academy of Sciences of the United States of America* 104: 5732–5737. https://doi.org/10.1073/pnas.0609812104.

Pollock, M. M., T. J. Beechie, J. M. Wheaton, et al. 2014. "Using Beaver Dams to Restore Incised Stream Ecosystems." *Bioscience* 64: 279–290. https://academic.oup.com/bioscience/article/64/4/279/2754168.

Pollock, M. M., G. Lewallen, K. Woodruff, C. E. Jordan, and J. M. Castro, eds. 2015. *The Beaver Restoration Guidebook: Working With Beaver to Restore Streams, Wetlands, and Floodplains*, 189. Version 1.0. United States Fish and Wildlife Service. http://www.fws.gov/oregonfwo/ToolsForLandowners/RiverScience/Beaver.asp.

Pollock, M. M., J. M. Wheaton, N. Bouwes, C. Volk, N. Weber, and C. E. Jordan. 2012. *Working With Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed: Design Rationale and Hypotheses*. National Oceanic and Atmospheric Administration. Technical Memorandum no. NMFS-NWFSC-120.

Pollock, M. M., S. Witmore, and E. Yokel. 2022. "Field Experiments to Assess Passage of Juvenile Salmonids Across Beaver Dams During Low Flow Conditions in a Tributary to the Klamath River, California, USA." *PLoS One* 17: e0268088. https://doi.org/10.1371/journal.pone.0268088.

Polvi, L. E., and E. Wohl. 2012. "The Beaver Meadow Complex Revisited – The Role of Beavers in Post-Glacial Floodplain Development." *Earth Surface Processes and Landforms* 37: 332–346. https://doi.org/10.1002/esp.2261.

Pourghasemi, H. R., S. Yousefi, N. Sadhasivam, and S. Eskandari. 2020. "Assessing, Mapping, and Optimizing the Locations of Sediment Control Check Dams Construction." *Science of the Total Environment* 739: 139954. https://doi.org/10.1016/j.scitotenv.2020.139954.

Puttock, A., H. A. Graham, J. Ashe, D. J. Luscombe, and R. E. Brazier. 2021. "Beaver Dams Attenuate Flow: A Multi-Site Study." *Hydrological Processes* 35: e14017. https://doi.org/10.1002/hyp.14017.

Puttock, A., H. A. Graham, D. Carless, and R. E. Brazier. 2018. "Sediment and Nutrient Storage in a Beaver Engineered Wetland." *Earth Surface Processes and Landforms* 43: 2358–2370. https://doi.org/10.1002/esp.4398.

Puttock, A., H. A. Graham, A. M. Cunliffe, M. Elliott, and R. E. Brazier. 2017. "Eurasian Beaver Activity Increases Water Storage, Attenuates Flow and Mitigates Pollution From Intensively Managed Grasslands." *Science of the Total Environment* 576: 430–443. https://www.sciencedirect.com/science/article/pii/S0048969716323099.

Qin, X., H. Zhu, Y. Ren, et al. 2022. "Erosion Intensity and Check Dam Size Affect the Horizontal and Vertical Distribution of Soil Particles, Carbon and Nitrogen: Evidence From China's Loess Plateau." *Catena* 217: 106451. https://doi.org/10.1016/j.catena.2022.106451.

Rango, A., and K. Havstad. 2011. "Review of Water-Harvesting Techniques to Benefit Forage Growth and Livestock on Arid and Semiarid Rangelands." In *Water Conservation*, edited by M. K. Jha, 1–18. IntechOpen.

Ray, A. M., A. J. Rebertus, and H. L. Ray. 2001. "Macrophyte Succession in Minnesota Beaver Ponds." *Canadian Journal of Botany* 79: 487–499. https://doi.org/10.1139/b01-018.

Records, R. M., E. Wohl, and M. Arabi. 2016. "Phosphorus in the River Corridor." *Earth-Science Reviews* 158: 65–88. https://doi.org/10.1016/j.earscirev.2016.04.010.

Rees, J. C., K. B. Lininger, J. D. Landis, and C. E. Briles. 2024. "Assessing Controls on Sedimentation Rates and Sediment Organic

Carbon Accretion in Beaver Ponds." *Science of the Total Environment* 949: 174951. https://doi.org/10.1016/j.scitotenv.2024.174951.

Renwick, W. H., S. V. Smith, J. D. Bartley, and R. W. Buddemeier. 2005. "The Role of Impoundments in the Sediment Budget of the Conterminous United States." *Geomorphology* 71: 99–111. https://doi.org/10.1016/j.geomorph.2004.01.010.

Ricci, G. F., G. Romano, V. Leronni, and F. Gentile. 2019. "Effect of Check Dams on Riparian Vegetation Cover: A Multiscale Approach Based on Field Measurements and Satellite Images for Leaf Area Index Assessment." *Science of the Total Environment* 657: 827–838. https://doi.org/10.1016/j.scitotenv.2018.12.081.

Riggsbee, J. A., R. Wetzel, and M. W. Doyle. 2012. "Physical and Plant Community Controls on Nitrogen and Phosphorus Leaching From Impounded Riverine Wetlands Following Dam Removal." *River Research and Applications* 28: 1439–1450. https://doi.org/10.1002/rra.1536.

Rolauffs, P., D. Hering, and S. Lohse. 2001. "Composition, Invertebrate Community and Productivity of a Beaver Dam in Comparison to Other Stream Habitat Types." *Hydrobiologia* 459: 201–212. https://doi.org/10.1023/A:1012507613952.

Romansic, J. M., N. L. Nelson, K. B. Moffett, and J. Piovia-Scott. 2021. "Beaver Dams Are Associated With Enhanced Amphibian Diversity via Lengthened Hydroperiods and Increased Representation of Slow-Developing Species." *Freshwater Biology* 66: 481–494. https://doi.org/10.1111/fwb.13654.

Ronnquist, A. L., and C. J. Westbrook. 2021. "Beaver Dams: How Structure, Flow State, and Landscape Setting Regulate Water Storage and Release." *Science of the Total Environment* 785: 147333. https://doi.org/10.1016/j.scitotenv.2021.147333.

Rosell, F., O. Bozser, P. Collen, and H. Parker. 2005. "Ecological Impact of Beavers *Castor fiber* and *Castor canadensis* and Their Ability to Modify Ecosystems." *Mammal Review* 35: 248–276. https://doi.org/10.1111/j.1365-2907.2005.00067.x.

Russell, K. R., C. E. Moorman, J. K. Edwards, B. S. Metts, and D. C. Guynn. 1999. "Amphibian and Reptile Communities Associated With Beaver (*Castor canadensis*) Ponds and Unimpounded Streams in the Piedmont of South Carolina." *Journal of Freshwater Ecology* 14: 149–158. https://doi.org/10.1080/02705060.1999.9663666.

Scamardo, J., and E. Wohl. 2020. "Sediment Storage and Shallow Groundwater Response to Beaver Dam Analogues in the Colorado Front Range, USA." *River Research and Applications* 36: 398–409. https://doi.org/10.1002/rra.3592.

Schmiedel, U., M. Kruspe, L. Kayser, and N. Oettle. 2017. "The Ecological and Financial Impact of Soil Erosion and Its Control – A Case Study From the Semiarid Northern Cape Province, South Africa." *Land Degradation & Development* 28: 74–82. https://doi.org/10.1002/ldr.2513.

Schultz, H. 2023. "Beaver Dam Analogs (BDAs) Alter Carbon Pools, Fluxes, and Concentrations of Intermountain Headwater Streams." MS thesis, University of Montana. https://scholarworks.umt.edu/etd/12198/.

Schwindt, S., M. H. Franca, G. De Cesare, and A. J. Schleiss. 2017. "Analysis of Mechanical-Hydraulic Bedload Deposition Control Measures." *Geomorphology* 295: 467–479. https://doi.org/10.1016/j.geomorph.2017.07.020.

SCS (Soil and Water Conservation Service). 1982. "Ponds – Planning, Design, Construction." In *Agriculture Handbook 590*. USDA Soil Conservation Service.

Sferra, C. O., J. L. Hart, and J. G. Howeth. 2017. "Habitat Age Influences Metacommunity Assembly and Species Richness in Successional Pond Ecosystems." *Ecosphere* 8: e01871. https://doi.org/10.1002/ecs2.1871.

Shannon, K. C., N. R. Christman, B. C. Crump, et al. 2023. "Comparing Sediment Microbial Communities of Arctic Beaver Ponds to Tundra Lakes and Streams." *Journal of Geophysical Research: Biogeosciences* 128, no. 8: e2023JG007408. https://doi.org/10.1029/2023JG007408.

Sherman, M., J. Hripto, E. K. Peck, et al. 2022. "Backed-Up, Saturated, and Stagnant: Effect of Milldams on Upstream Riparian Groundwater Hydrologic and Mixing Regimes." *Water Resources Research* 58: e2022WR033038. https://doi.org/10.1029/2022WR033038.

Shieh, C. L., Y. R. Guh, and S. Q. Wang. 2007. "The Application of Range of Variability Approach to the Assessment of a Check Dam on Riverine Habitat Alteration." *Environmental Geology* 52: 427–435. https://doi.org/10.1007/s00254-006-0470-3.

Simmons, S. 2024. "The Impact of Low-Head Dams on Freshwater Turtle Species Assemblages." MS thesis, Indiana State University.

Singer, E. E., and M. M. Gangloff. 2011. "Effects of a Small Dam on Freshwater Mussel Growth in an Alabama (U.S.A.) Stream." *Freshwater Biology* 56: 1904–1915. https://doi.org/10.1111/j.1365-2427.2011.02608.x.

Smith, J. M., and M. E. Mather. 2013. "Beaver Dams Maintain Fish Biodiversity by Increasing Habitat Heterogeneity Throughout a Low-Gradient Stream Network." *Freshwater Biology* 58: 1523–1538. https://doi.org/10.1111/fwb.12153.

Smufer, F., J. P. Casas-Ruiz, A. St. Pierre, and P. A. del Giorgio. 2023. "Integrating Beaver Ponds Into the Carbon Emission Budget of Boreal Aquatic Networks: A Case Study at the Watershed Scale." *Ecosystems* 26: 1309–1325. https://doi.org/10.1007/s10021-023-00835-3.

Snodgrass, J. W., and G. K. Meffe. 1998. "Influence of Beavers on Stream Fish Assemblages: Effects of Pond Age and Watershed Position." *Ecology* 79: 928–942. https://doi.org/10.1890/0012-9658(1998)079[0928;IOBOSF]2.0.CO;2.

Sobek, S., T. DelSontro, N. Wongfun, and B. Wehrli. 2012. "Extreme Organic Carbon Burial Fuels Intense Methane Bubbling in a Temperate Reservoir." *Geophysical Research Letters* 39, no. 1: 2011GL050144. https://doi.org/10.1029/2011GL050144.

Sor, R., P. B. Ngor, S. Lek, et al. 2023. "Fish Biodiversity Declines With Dam Development in the Lower Mekong Basin." *Scientific Reports* 13: 8571. https://www.nature.com/articles/s41598-023-35665-9.

Sousa, R., J. G. Nogueira, M. Lopes-Lima, S. Varandas, and A. Teixeira. 2019. "Water Mill Canals as Habitat for *Margaritifera margaritifera*: Stable Refuge or an Ecological Trap?" *Ecological Indicators* 106: 105469. https://doi.org/10.1016/j.ecolind.2019.105469.

Spinti, R. A., L. E. Condon, and J. Zhang. 2023. "The Evolution of Dam Induced River Fragmentation in the United States." *Nature Communications* 14: 3820. https://doi.org/10.1038/s41467-023-39194-x.

Stanford, J. A., M. S. Lorang, and F. R. Hauer. 2005. "The Shifting Habitat Mosaic of River Ecosystems." *Internationale Vereinigung fur Theoretische und Angewandte Limnologie: Verhandlungen* 39: 123–136. https://doi.org/10.1080/03680770.2005.11901979.

Stringer, A. P., and M. J. Gaywood. 2016. "The Impacts of Beavers *Castor* Spp. on Biodiversity and the Ecological Basis for Their Reintroduction to Scotland, UK." *Mammal Review* 46: 270–283. https://doi.org/10.1111/mam.12068.

Sundell, J., W. Liao, and P. Nummi. 2021. "Small Mammal Assemblage in Beaver-Modified Habitats." *Mammal Research* 66: 181–186. https://doi.org/10.1007/s13364-020-00545-4.

Suriyawong, P., D. Thapanya, E. A. Bergey, and P. Chantaramongkol. 2018. "Aquatic Insect Functional Feeding Groups in a Mountain Stream With a Series of Check Dams in Northern Thailand." *Sains Malaysiana* 47: 1379–1386. https://doi.org/10.17576/jsm-2018-4707-04.

Szatten, D., M. Brzezińska, M. Maerker, Z. Podgórski, and D. Brykała. 2023. "Natural Landscapes Preferred for the Location of Past Watermills and Their Predisposition to Preserve Cultural Landscape Enclaves." *Anthropocene* 42: 100376. https://doi.org/10.1016/j.ancene.2023.100376.

Taylor, B. R., C. MacInnis, and T. A. Floyd. 2010. "Influence of Rainfall and Beaver Dams on Upstream Movement of Spawning Atlantic Salmon in a Restored Brook in Nova Scotia, Canada." *River Research and Applications* 26: 183–193. https://doi.org/10.1002/rra.1252.

Tiedje, J. M. 1988. "Ecology of Denitrification and Dissimilatory Nitrate Reduction to Ammonium." In *Environmental Microbiology of Anaerobes*, edited by A. B. J. Zehnder, 179–244. John Wiley & Sons.

Wade, J., L. Lautz, C. Kelleher, et al. 2020. "Beaver Dam Analogues Drive Heterogeneous Groundwater-Surface Water Interactions." *Hydrological Processes* 34: 5340–5353. https://doi.org/10.1002/hyp.13947.

Walter, R. C., and D. J. Merritts. 2008. "Natural Streams and the Legacy of Water-Powered Mills." *Science* 319: 299–304. https://doi.org/10.1126/science.1151716.

Wang, F., Y. Lang, C. Q. Liu, Y. Qin, N. Yu, and B. Wang. 2019. "Flux of Organic Carbon Burial and Carbon Emissions From a Large Reservoir: Implications for the Cleanliness Assessment of Hydropower." *Science Bulletin* 64: 603–611. https://doi.org/10.1016/j.scib.2019.03.034.

Wang, X., E. L. Shaw, C. J. Westbrook, and A. Bedard-Haughn. 2018. "Beaver Dams Induce Hyporheic and Biogeochemical Changes in Riparian Areas in a Mountain Peatland." *Wetlands* 38: 1017–1032. https://doi.org/10.1007/s13157-018-1059-9.

Ward, J. V., K. Tockner, and F. Schiemer. 1999. "Biodiversity of Floodplain River Ecosystems: Ecotones and Connectivity." *Regulated Rivers: Research and Management* 15: 125–139. https://doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3%3C125::AID-RRR523%3E3.0.CO;2-E.

Wegener, P., T. Covino, and E. Wohl. 2017. "Beaver-Mediated Lateral Hydrologic Connectivity, Fluvial Carbon and Nutrient Flux, and Aquatic Ecosystem Metabolism." *Water Resources Research* 53: 4606–4623. https://doi.org/10.1002/2016WR019790.

Weil, R. R., and N. C. Brady. 2017. *The Nature and Properties of Soils*. 15th ed. Pearson Publishers.

Weitzman, J. N., K. J. Forshay, J. P. Kaye, P. M. Mayer, J. C. Koval, and R. C. Walter. 2014. "Potential Nitrogen and Carbon Processing in a Landscape Rich in Milldam Legacy Sediments." *Biogeochemistry* 120: 337–357. https://doi.org/10.1007/s10533-014-0003-1.

Weitzman, J. N., and J. P. Kaye. 2017. "Nitrate Retention Capacity of Milldam-Impacted Legacy Sediments and Relict A Horizon Soils." *Soil* 3: 95–112. https://doi.org/10.5194/soil-3-95-2017.

Westbrook, C. J., and D. J. Cooper. 2024. "Comparing the Sources of Sediment Retained by Beaver Dams and Beaver Dam Analogs." *Water Resources Research* 60: e2024WR037717. https://doi.org/10.1029/2024WR037717.

Westbrook, C. J., D. J. Cooper, and B. W. Baker. 2006. "Beaver Dams and Overbank Floods Influence Groundwater-Surface Water Interactions of a Rocky Mountain Riparian Area." *Water Resources Research* 42, no. 6: 2005WR004560. https://doi.org/10.1029/2005WR004560.

Westbrook, C. J., D. J. Cooper, and B. W. Baker. 2011. "Beaver Assisted River Valley Formation." *River Research and Applications* 27: 247–256. https://doi.org/10.1002/rra.1359.

Wikander, O. 2000. *Handbook of Ancient Water Technology*, 371–400. Brill. https://doi.org/10.1163/9789004473829_019.

Wikar, Z., M. Ciechanowski, and A. Zwolicki. 2024. "The Positive Response of Small Terrestrial and Semi-Aquatic Mammals to Beaver Damming." *Science of the Total Environment* 906: 167568. https://doi.org/10.1016/j.scitotenv.2023.167568.

Willby, N. J., A. Law, O. Levanoni, G. Foster, and F. Ecke. 2018. "Rewilding Wetlands: Beaver as Agents of Within-Habitat Heterogeneity and the Responses of Contrasting Biota." *Philosophical Transactions of the Royal Society, B: Biological Sciences* 373: 20170444. https://doi.org/10.1098/rstb.2017.0444.

Wilson, J. B., and S. Bremner-Harrison. 2025. "A Systematic Literature Review Investigating the Association Between Biodiversity and Beaver Lodges." *Mammal Review* 55: e12363. https://doi.org/10.1111/mam.12363.

Wilson, R. T. 2007. "Perceptions, Practices, Principles and Policies in Provision of Livestock Water in Africa." *Agricultural Water Management* 90: 1–12. https://www.sciencedirect.com/science/article/abs/pii/S0378377407000728.

Wohl, E. 2013. "Landscape-Scale Carbon Storage Associated With Beaver Dams." *Geophysical Research Letters* 40: 3631–3636. https://doi.org/10.1002/grl.50710.

Wohl, E. 2021. "Legacy Effects of Loss of Beavers in the Continental United States." *Environmental Research Letters* 16: 025010. https://doi.org/10.1088/1748-9326/abd34e.

Wohl, E. 2024. "Resilience in River Corridors: How Much Do We Need?" *Perspectives of Earth and Space Scientists* 5: e2023CN000226. https://doi.org/10.1029/2023CN000226.

Wohl, E., J. Castro, B. Cluer, et al. 2021. "Rediscovering, Reevaluating, and Restoring Lost River-Wetland Corridors." *Frontiers in Earth Science* 9: 653623. https://doi.org/10.3389/feart.2021.653623.

Wohl, E., K. Dwire, N. Sutfin, L. Polvi, and R. Bazan. 2012. "Mechanisms of Carbon Storage in Mountainous Headwaters." *Nature Communications* 3: 1263. https://doi.org/10.1038/ncomms2274.

Wohl, E., A. E. Marshall, J. Scamardo, D. White, and R. R. Morrison. 2022. "Biogeomorphic Influences on River Corridor Resilience to Wildfire Disturbances in a Mountain Streams of the Southern Rockies, USA." *Science of the Total Environment* 820: 153321. https://doi.org/10.1016/j.scitotenv.2022.153321.

Wohl, E., and D. N. Scott. 2017. "Wood and Sediment Storage and Dynamics in River Corridors." *Earth Surface Processes and Landforms* 42: 5–23. https://doi.org/10.1002/esp.3909.

Wolf, J. M., and E. Hammill. 2023. "Provisioning of Breeding Habitat by Beaver and Beaver Dam Analogue Complexes Within the Great Salt Lake Catchment." *Freshwater Biology* 68: 659–673. https://doi.org/10.1111/fwb.14054.

Wood, P. J., and S. Barker. 2000. "Old Industrial Mill Ponds: A Neglected Ecological Resource." *Applied Geography* 20: 65–81. https://doi.org/10.1016/S0143-6228(99)00015-6.

Wright, J. P., C. G. Jones, and A. S. Flecker. 2002. "An Ecosystem Engineer, the Beaver, Increases Species Richness at the Landscape Scale." *Oecologia* 132: 96–101. https://link.springer.com/article/10.1007/s00442-002-0929-1.

Xia, X., S. Zhang, S. Li, et al. 2018. "The Cycle of Nitrogen in River Systems: Sources, Transformation, and Flux." *Environmental Science: Processes & Impacts* 20, no. 6: 863–891. https://doi.org/10.1039/C8EM00042E.

Yang, N., C. Zhang, L. Wang, et al. 2021. "Nitrogen Cycling Processes and the Role of Multi-Trophic Microbiota in Dam-Induced River-Reservoir Systems." *Water Research* 206: 117730. https://doi.org/10.1016/j.watres.2021.117730.

Yao, Y., J. Song, and X. Wei. 2022. "The Fate of Carbon in Check Dam Sediments." *Earth-Science Reviews* 224: 103889. https://doi.org/10.1016/j.earscirev.2021.103889.

Zema, D. A., G. Bombino, P. Denisi, M. E. Lucas-Borja, and S. M. Zimbone. 2018. "Evaluating the Effects of Check Dams on Channel Geometry, Bed Sediment Size and Riparian Vegetation in Mediterranean Mountain Torrents." *Science of the Total Environment* 642: 327–340. https://doi.org/10.1016/j.scitotenv.2018.06.035.

Zhang, A. T., J. Urpelainen, and W. Schlenker. 2018. *Power of the River: Introducing the Global Dam Tracker (GDAT)*. Columbia University, Center on Global Energy Policy. https://www.energypolicy.columbia.edu/wp-content/uploads/2018/11/GlobalDams_CGEP_2018.pdf.

Zhang, H., S. Liu, W. Yuan, et al. 2016. "Loess Plateau Check Dams Can Potentially Sequester Eroded Soil Organic Carbon." *Journal of Geophysical Research: Biogeosciences* 121: 1449–1455. https://doi.org/10.1002/2016JG003348.

Zhao, Y., and L. Wang. 2021. "Determination of Groundwater Recharge Processes and Evaluation of the 'Two Water Worlds' Hypothesis at a Check Dam on the Loess Plateau." *Journal of Hydrology* 595: 125989. https://doi.org/10.1016/j.jhydrol.2021.125989.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplemental Table 1. Comparative values for selected dam characteristics [values in red brackets are total reported range]

Characteristic[1]	**Beaver dam**	**Beaver dam analogue**	**Mill dam**	**Check dam**	**Stock ponds**
Contributing drainage area (km^2)	3.4 (0.0045-103); Dunn et al., 2024 6.5-178.7; Rees et al., 2024 72; Green & Westbrook, 2009 13-335; Nagle, 2024 [0.004-335]	5.9-443; Nagle, 2024 4.1, 8.1; Scamardo & Wohl, 2020 710; Davee et al., 2019 1.6-9.4; Norman, 2020 2500; Orr et al., 2020 92; Hansen, 2024 12 (10-23); Dunn et al., 2024 [1.6-2500]	Mostly < 200 km^2; Bishop & Muñoz-Salinas, 2013 77; Platt et al., 2024 1.8-100; Donovan et al., 2016 [1.8-200]	12-415; Bombino et al., 2022 0.3-27; Fang et al., 2019 0.2; Zhao et al., 2017 0.01-4.4; Boix-Fayos et al., 2008 5.7; Galia et al., 2021 0.4-0.6; Nyssen et al., 2004 0.34-1.6; Nichols, 2006 0.03-0.04; Polyakov et al., 2014 [0.01-415]	0.08-10 km^2; Womack, 2012 0.5-2.3 km^2; Neff, 1980 0.5 km^2; Powell et al., 2007 0.2-9.8 km^2; Gottschalk, 1947 [0.08-10]
Dam height (m)	0.4-1.0; Rees et al., 2024 0.6 (0.4-1.0); Nagle, 2024 0.3-1.4; Wolf, 2023 [0.3-1.4]	0.8 (0.3-1.6); Nagle, 2024 0.2-0.8; Scamardo & Wohl, 2020 0.2-2; Wolf, 2023 [0.2-2]	2.4 (1.5-9); Merritts et al., 2013 6; Platt et al., 2024 1.8-6.4; Donovan et al., 2016 [1.5-9]	< 3 to > 15; Lucas-Borja et al., 2021 2.5 (1.5-4); Pourghasemi et al., 2020 1-1.1; Galia et al., 2021 0.8-1.1; Nyssen et al., 2004 [0.8-15]	1.8-7.8 m; Womack, 2012 2-4 m; Florsheim et al., 2013 [1.8-7.8]
Sediment storage volume (m^3)	913 (6-5434); Dunn et al., 2024 876-6355; Butler, 2012 98-842; Green & Westbrook, 2009	1.2-4.1, 1.1-3.2; Scamardo & Wohl, 2020 0.6 (0.1-5.0); Hansen, 2024 12 (4-27); Dunn et al., 2024	643; Bishop et al., 2010 22,300 & 29,240 & 77,000; Merritts et al., 2013 14,530-16,060; Platt et al., 2024	7364-13,490; Bombino et al., 2022 27 (0.2-238); Lucas-Borja et al., 2018 48-15,140; Boix-Fayos et al., 2008	114-437; Powell et al., 2007 [114-437]

	33-516; John & Klein, 2004 11-5084; Butler & Malanson, 1995 9-267; Meentemeyer & Butler, 1999 [6-6355]	0, 34; Orr et al., 2020 [0-34]	[643-77,000]	155,849; Yafeng et al., 2009 360-11,015; Nichols, 2006 [0.2-155,849]	
Spacing density (dams/100 m of river)	0.03-0.18; Butler & Malanson, 1995 0.04; Wolf, 2023 0.02; Kornse & Wohl, 2020 0.08 (Cochetopa Creek, Colorado, USA, Google Earth survey across entire river corridor) [2-18]	0.03; Broderius, 2021 0.02; Wade et al., 2020 0.01, 0.03; Scamardo and Wohl, 2020 0.01; Munir & Westbrook, 2021 0.03; Davee et al., 2019 0.03, 0.04; Wolf, 2023 0.001-0.01; Orr et al., 2020 0.02; Hansen, 2024 [0.1-4]	0.0002-0.0006; Merritts et al., 2013 [0.02-0.06]	0.07-0.09; Lenzi & Comiti, 2003 0.01; Galia et al., 2021 0.3-0.4; Nyssen et al., 2004 0.0003; Conesa-Garcia et al., 2007 6-12; Polyakov et al., 2014 [0.03-40]	~0.05-0.01; Florsheim et al., 2013 0.05-0.2[2] [0.05-0.2]

[1] where reference includes multiple dams, median value is given with range in parentheses

[2] stock ponds are more likely to be reported in densities of dams per km^2; these linear values were obtained using Google Earth to identify stock ponds & measure streams lengths in semiarid regions of Colorado and Wyoming, USA

References

Bishop, P., Muñoz-Salinas, E., MacKenzie, A.B., Pulford, I., McKibbin, J., 2010. The character, volume and implications of sediment impounded in mill dams in Scotland: the case of the Baldernock Mill dam in East Dunbartonshire. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 101, 97-110. https://doi.org/10.1017/S1755691010009205

Bishop, P., Muñoz-Salinas, E., 2013. Tectonics, geomorphology and water mill location in Scotland, and the potential impacts of mill dam failure. Applied Geography 42, 195-205. https://doi.org/10.1016/j.apgeog.2013.04.010

Boix-Fayos, C., de Vente, J., Martinez-Mena, M., Barbera, G.G., Castillo, V., 2008. The impact of land use change and check-dams on catchment sediment yield. Hydrological Processes 22, 4922-4935. https://doi.org/10.1002/hyp.7115

Bombino, G., Barbaro, G., D'Agostino, D., Denisi, P., Labate, A., Zimbone, S.M., 2022. A method for estimating stored sediment volumes by check dam systems at the watershed level: Example of an application in a Mediterranean environment. Journal of Soils and Sediments 22, 1329-1343. https://doi.org/10.1007/s11368-022-03163-6

Broderius, N.D., 2021. Effects of beaver dam analogs on stream ecosystem function of Crab Creek, Washington State. MS thesis, Eastern Washington University, Cheney, WA https://dc.ewu.edu/theses/727/

Butler, D.R., 2012. Characteristics of beaver ponds on deltas in a mountain environment. Earth Surface Processes and Landforms 37, 876-882. https://doi.org/10.1002/esp.3218

Butler, D.R., Malanson, G.P., 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology 13, 255-269. https://doi.org/10.1016/0169-555X(95)00031-Y

Conesa-García, C., Lopez-Bermudez, F., Garcial-Lorenzo, R., 2007. Bed stability variations after check dam construction in torrential channels (south-east Spain). Earth Surface Processes and Landforms 32, 2165-2184. https://doi.org/10.1002/esp.1521

Davee, R., Gosnell, H., Charnley, S., 2019. Using beaver dam analogues for fish and wildlife recovery on public and private rangelands in eastern Oregon. USDA Pacific Northwest Research Station, Research Paper PNW-RP-612.

Donovan, M., Miller, A., Baker, M., 2016. Reassessing the role of milldams in Piedmont floodplain development and remobilization. Geomorphology 268, 133-145. https://doi.org/10.1016/j.geomorph.2016.06.007

Dunn, S.B., Rathburn, S.L., Wohl E., 2024. Post-fire sediment attenuation in beaver ponds, Rocky Mountains, CO and WY, USA. Earth Surface Processes and Landforms 49, 4340-4354. https://doi.org/10.1002/esp.5970

Fang, N.F., Zeng, Y., Ni, L.S., Shi, Z.H., 2019. Estimation of sediment trapping behind check dams using high-density electrical resistivity tomography. Journal of Hydrology 568, 1007-1016. https://doi.org/10.1016/j.jhydrol.2018.11.062

Florsheim, J.L., Chin, A., Nichols, A., 2013. Effects of multiple small stock-pond dams in a coastal watershed in central California: Implications for removing small dams for restoration, in: De Graff, J.V., Evans, J.E. (Eds.), The Challenges of Dam Removal and River Restoration. GSA Reviews in Engineering Geology, Geological Society of America, Boulder, CO. https://doi.org/10.1130/2013.4121(12)

Galia, T., Skarpich, V., Ruman, S., 2021. Impact of check dam series on coarse sediment connectivity. Geomorphology 377, 107595. https://doi.org/10.1016/j.geomorph.2021.107595

Gottschalk, L.C., 1947. A method of estimating sediment accumulation in stock ponds. Transactions, American Geophysical Union 28, 621-625. https://doi.org/10.1029/TR028i004p00621

Green, K.C., Westbrook, C.J., 2009. Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. BC Journal of Ecosystems and Management 10, 68-79. https://doi.org/10.22230/jem.2009v10n1a412

Hansen, G., 2024. A comparison of sediment accumulation effectiveness behind beaver dam analogues, one rock dams, and post-assisted log structures on East Foster Creek, Douglas County, Washington. MS thesis, Central Washington University, Ellensburg, WA.

John, S., Klein, A., 2004. Hydrogeomorphic effects of beaver dams on floodplain morphology: avulsion processes and sediment fluxes in upland valley floors (Spessart, Germany). Quaternaire 15, 219-231.

Kornse, Z., Wohl, E., 2020. Assessing restoration potential for beaver (*Castor canadensis*) in the semiarid foothills of the Southern Rockies, USA. River Research and Applications 36, 1932-1943. https://doi.org/10.1002/rra.3719

Lenzi, M.A., Comiti, F., 2003. Local scouring and morphological adjustments in steep channels with check-dam sequences. Geomorphology 55, 97-109. https://doi.org/10.1016/S0169-555X(03)00134-X

Lucas-Borja, M.E., Zema, D.A., Guzman, M.D.H., Yang, Y., Hernandez, A.C., Xiangzhou, X., Carra, B.G., Nichols, M., Cerda, A., 2018. Exploring the influence of vegetation cover, sediment storage capacity and channel dimensions on stone check dam conditions and effectiveness in a large regulated river in Mexico. Ecological Engineering 122, 39-47. https://doi.org/10.1016/j.ecoleng.2018.07.025

Lucas-Borja, M.E., Piton, G., Yu, Y., Castillo, C., Zema, D.A., 2021. Check dams worldwide: Objectives, functions, effectiveness and undesired effects. Catena 204, 105390. https://doi.org/10.1016/j.catena.2021.105390

Meentemeyer, R.K., Butler, D.R., 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. Physical Geography 20, 436-446. https://doi.org/10.1080/02723646.1999.10642688

Merritts, D., Walter, R., Rahnis, M., Cox, S., Hartranft, J., Scheid, C., Potter, N., Jenschke, M., Reed, A., Matuszewski, D., Kratz, L., Manion, L., Shilling, A., Datin, K., 2013. The rise and fall of Mid-Atlantic streams: Millpond sedimentation, milldam breaching, channel incision, and stream bank erosion, in: De Graff, J.V., Evans, J.E. (Eds.), The Challenges of Dam Removal and River Restoration. GSA Reviews in Engineering Geology, Geological Society of America, Boulder, CO. https://doi.org/10.1130/2013.4121(14)

Munir, T.M., Westbrook, C.J., 2021. Beaver dam analogue configurations influence stream and riparian water table dynamics of a degraded spring-fed creek in the Canadian Rockies. River Research and Applications 37, 330-342. https://doi.org/10.1002/rra.3753

Nagle, S., 2024. Dam dimensions and surface porosity affect the water storage capacity of beaver dam analogs compared to natural beaver dams. MS thesis, Eastern Washington University, Cheney, WA. https://dc.ewu.edu/theses/939/

Neff, E.L., 1980. Using sodium carbonate to seal leaky stock ponds in eastern Montana. Journal of Range Management 33, 292-295.

Nichols, M.H., 2006. Measured sediment yield rates from semiarid rangeland watersheds. Rangeland Ecology and Management 59, 55-62. https://doi.org/10.2111/05-075R1.1

Norman, E.G., 2020. Hydrologic response of headwater streams restored with beaver dam analogue structures. MS thesis, Montana Technological University, Butte, MT. https://www.proquest.com/openview/a78737790293188b967dff5c1d622e7f/1?pq-origsite=gscholar&cbl=18750&diss=y

Nyssen, J., Veyret-Picot, M., Poesen, J., Moeyersons, J., Haile, M., Deckers, J., Govers, G., 2004. The effectiveness of loose rock check dams for gully control in Tigray, northern Ethiopia. Soil Use and Management 20, 55-64. https://doi.org/10.1111/j.1475-2743.2004.tb00337.x

Orr, M.R., Weber, N.P., Noone, W.N., Mooney, M.G., Oakes, T.M., Broughton, H.M., 2020. Short-term stream and riparian responses to beaver dam analogs on a low-gradient channel lacking woody riparian vegetation. Northwest Science 93, 171-184. https://doi.org/10.3955/046.093.0302

Platt, J.R., Martin, D.J., Armstrong, W.H., Mayfield, M.W., 2024. Geomorphic response to the removal of the Ward's Mill Dam on the Watauga River, North Carolina. Southeastern Geographer 64, 165-186. https://dx.doi.org/10.1353/sgo.2024.a929404

Polyakov, V.O., Nichols, M.H., McClaran, M.P., Nearing, M.A., 2014. Effect of check dams on runoff, sediment yield, and retention on small semiarid watersheds. Journal of Soil and Water Conservation 69, 414-421. doi:10.2489/jswc.69.5.414

Pourghasemi, H.R., Yousefi, S., Sadhasivam, N., Eskandari, S., 2020. Assessing, mapping, and optimizing the locations of sediment control check dams construction. Science of the Total Environment 739, 139954. https://doi.org/10.1016/j.scitotenv.2020.139954

Powell, D.M., Brazier, R., Parsons, A., Wainwright, J., Nichols, M., 2007. Sediment transfer and storage in dryland headwater streams. Geomorphology 88, 152-166. https://doi.org/10.1016/j.geomorph.2006.11.001

Rees, J.C., Lininger, K.B., Landis, J.D., Briles, C.E., 2024. Assessing controls on sedimentation rates and sediment organic carbon accretion in beaver ponds. Science of the Total Environment 949, 174951. https://doi.org/10.1016/j.scitotenv.2024.174951

Scamardo, J., Wohl, E., 2020. Sediment storage and shallow groundwater response to beaver dam analogues in the Colorado Front Range, USA. River Research and Applications 36, 398-409. https://doi.org/10.1002/rra.3592

Wade, J., Lautz, L., Kelleher, C., Vidon, P., Davis, J., Beltran, J., Pearce, C., 2020. Beaver dam analogues drive heterogeneous groundwater-surface water interactions. Hydrological Processes 34, 5340-5353. https://doi.org/10.1002/hyp.13947

Wolf, J.M., 2023. Analyzing the impacts of beaver dam and beaver dam analog complexes to stream ecology within the Intermountain West. PhD dissertation, Utah State University, Logan, UT. https://digitalcommons.usu.edu/etd2023/3/

Womack, J.M., 2012. Evaluation of the hydrologic effects of stock ponds on a prairie watershed. MS thesis, Montana State University, Bozeman, MT. https://scholarworks.montana.edu/items/6e50a8bb-7eb2-427c-aa52-2ac355d4169b?show=full

Yafeng, W., Fu, B., Hou, F., Lu, Y., Lu, X., Song, C., Luan, Y., 2009. Estimation of sediment volume trapped by check-dam based on differential GPS technique. Transactions Chinese Society of Agricultural Engineering 25, 79-83. (Chinese except for abstract) https://www.ingentaconnect.com/content/tcsae/tcsae/2009/00000025/00000009/art00014#

Zhao, T.Y., Yang, M.Y., Walling, D.E., Zhang, F.B., Zhang, J.Q., 2017. Using check dam deposits to investigate recent changes in sediment yield in the Loess Plateau, China. Global and Planetary Change 152, 88-98. https://doi.org/10.1016/j.gloplacha.2017.03.003