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Trends in the Outcomes, Practice, and Law of Low-Tech Process-Based Restoration in Western Rangelands☆

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ABSTRACT

Low tech process-based restoration (LTPBR) is increasingly used to improve river corridor resilience to diverse stressors introduced by changing land use, climate, and water usage. However, the future of LTPBR depends on multiple physical, ecological, and social factors, including the influence of water availability on LTPBR outcomes and the legal capacity for future restoration in water-limited environments. A growing body of scientific and legal literature on LTPBR allows for a quantitative, regional comparison of LTPBR projects to understand: (1) How do physical characteristics of LTPBR projects (including structure type, number, and local setting) influence the magnitude of change following LTPBR? and (2) How are social dimensions related to practitioner attitudes and water law impacting LTPBR? We evaluated data from 65 LTPBR projects in the western U.S. that used natural beaver dams, beaver dam analogues, or one-rock dams to quantify trends in commonly measured outcomes with geographic location, project size, and local precipitation. We additionally reviewed water law in five states across the western U.S. and interviewed 13 restoration practitioners to consider the social dimensions of LTPBR. Results show that LTPBR projects significantly increased water storage, sediment storage, and riparian vegetation greenness, and that outcomes vary significantly with mean annual precipitation, time since restoration, and LTPBR type. Trends suggest that LTPBR could provide expected outcomes across western rangelands even amid changing water availability. Changes to state-level water laws and perceptions of social benefits of LTPBR could support the expansion of stream restoration in rangeland streams. More monitoring and collaborations are needed to better implement, manage, and understand LTPBR projects and outcomes.

Introduction

Healthy river corridors – including channels and floodplains (Harvey and Gooseff, 2015) – provide critical services to ecosystems, economies, and communities globally (e.g., Hanna et al., 2018; Petsch et al., 2023). In rangelands, which comprise over 70% of the western United States (Rigge et al., 2020), historical and modern changes to land use, water diversion, and regional climate have stressed river corridor health by changing the availability of water, sediment, and habitat (Grafton et al., 2010; Jaeger

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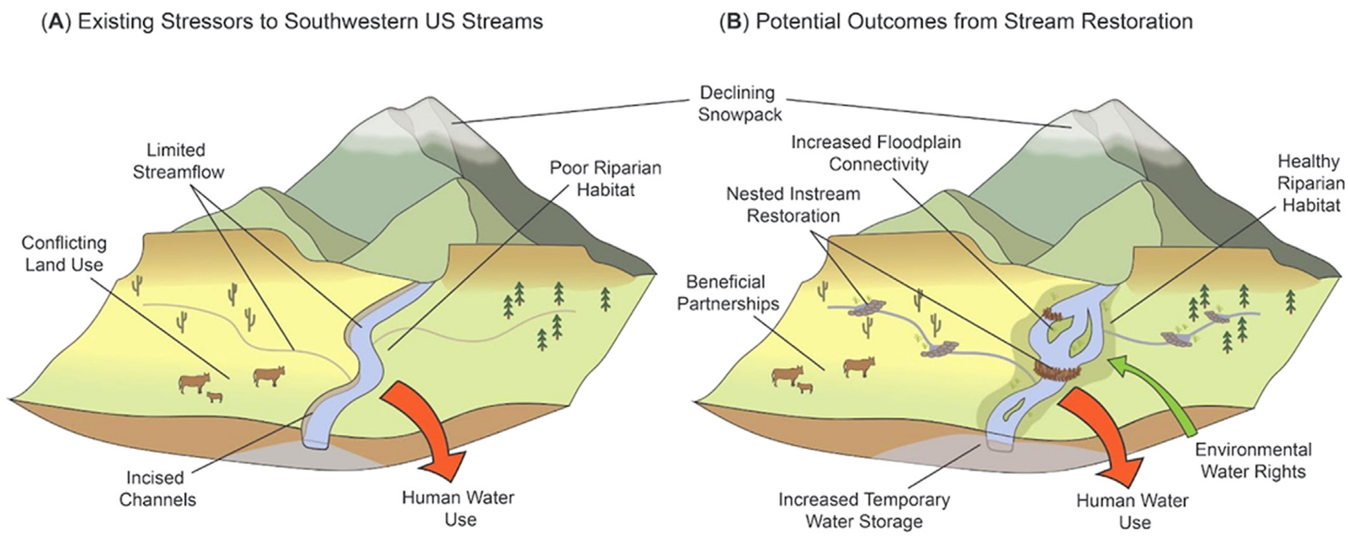

Figure 1. Conceptual diagram (not to scale) highlighting (A) anthropogenic and environmental stressors to headwater streams and downstream tributaries in the southwestern U.S., and (B) expected outcomes and benefits of instream, process-based restoration. Although restoration cannot remove or remediate all stressors, such as human water use and declining snowpacks, restoration is thought to slow and spread available water, which increases temporary water storage and reconnects streams and floodplains, allowing for riparian vegetation to thrive. Design by J. Scamardo.

et al., 2014; Reynolds et al., 2015). The historical over-trapping of beaver (*Castor canadensis*) – a keystone species and ecosystem engineer – following European settlement in the western U.S. caused widespread declines in beaver dam densities, which reduced water and sediment storage on the landscape and resulted in stream incision through former wetlands (Wohl, 2021; Scamardo et al., 2022). Concurrently, consequences of land use change (e.g., overgrazing) have shifted vegetation assemblages, similarly altering water and sediment runoff patterns and potentially spurring widespread arroyo formation across the West (e.g., Cooke and Reeves, 1976; Graf 1983). Infrastructure within river corridors, such as dams and levees (Graf, 1999; Knox et al., 2022), has changed the movement and supply of water and sediment to downstream river corridors, resulting in further well-documented changes in river morphology and riparian vegetation (e.g., Williams and Wolman, 1984; Friedman et al., 1998; Graf, 2006; Nichols et al., 2023). Declining water storage, stream degradation, and habitat loss due to anthropogenic changes on the landscape in the western U.S. are expected to be exacerbated by climate change (Garfin et al., 2014) as seasonal snowpack declines and evaporative demand increases (Stewart et al., 2004; Stewart et al., 2005; Siirila-Woodburn et al., 2021; Albano et al., 2022). Traditionally seasonal snowpacks are expected to diminish or become ephemeral in the next ~30-60 years across the western U.S., resulting in shifts from snow- to rain-dominated systems with cascading impacts on streamflow and water availability (Mote et al., 2018; Musselman et al., 2021; Siirila-Woodburn et al., 2021). Extreme events, such as droughts and wildfires associated with current and future climate change, are further stressing rivers by reducing riparian vegetation, increasing sediment export from the landscape, and altering water runoff patterns (Bond et al., 2008; Jager et al., 2021; Berdugo et al., 2022; Gomez Isaza et al., 2022). Overall, these varied and increasing stressors in the western U.S. are expected to decrease water quantity and quality in rangeland streams and consequently threaten dependent ecosystems and communities (Fig. 1A).

In response, stream restoration has grown into a multibillion-dollar industry in the past four decades (Bernhardt et al., 2005; Wohl et al., 2015; Rohr et al., 2018), and over which time restoration goals and techniques have shifted (Wohl et al., 2015). Contention over restoration practices that emphasized the maintenance of river forms, such as Natural Channel Design (Rosgen, 1994), was met with calls for increased use of process-based stream restoration (Simon et al., 2007; Lave et al., 2009). Process-based restoration (PBR) encompasses a range of stream rehabilitation practices – including the reintroduction of keystone species, the management of grazing pressures, and the reconnection of channels and floodplains (Fig. 1B) – aimed at restoring normative rates of physical, chemical, and biological processes (Beechie et al., 2010). A particular subset of PBR termed low-tech PBR (LTPBR) uses simple, low unit-cost structures made from wood and other natural materials to restore river corridor processes (Wheaton et al., 2019). Examples include natural beaver dams, which are encouraged by the reintroduction of beavers onto the landscape (Pilliod et al., 2018; Nash et al., 2021); beaver dam analogues (BDAs), which are human-made structures built of wood and stone to mimic natural beaver dams (Wheaton et al., 2019); and one-rock dams (ORDs), which are built by assembling a barrier of rocks across typically dry (ephemeral) channels (Norman et al., 2022) (Fig. 1B and 2). Due to the low cost and construction needs, LTPBR is increasingly used to restore streams across rangelands in the western U.S. (Pilliod et al., 2018; Weber et al., 2017).

Many studies have synthesized the geomorphic, hydrologic, and biotic outcomes following LTPBR (e.g., Grudzinski et al. (2022); Gibson and Olden, 2014; Ecke et al., 2017; Larsen et al., 2021; Nash et al., 2021; Jordan and Fairfax, 2022; Norman et al., 2022; Skidmore and Wheaton, 2022; Corday, 2024). Broadly, LTPBR has been shown to decrease streamflow velocities, allowing for the ponding of water and sediment upstream of the structures and the storage of nutrients and carbon, resulting in increased vegetation establishment and growth. These commonly cited outcomes of LTPBR are thought to help build resilience – defined here as the capacity to recover from a disturbance without significantly reducing ecosystem function – to changing water availability associated with land use change, water diversion, and climate change (Jordan and Fairfax, 2022; Norman et al., 2022; Skidmore and Wheaton, 2022). For example, ponding water increases temporary surface storage and groundwater recharge, which may increase baseflow and the duration of streamflow (Poff et al., 1997; Burns and McDonnell 1998; Brogan et al., 2022). Decreasing streamflow velocity can temporarily increase water residence time, cycling of carbon

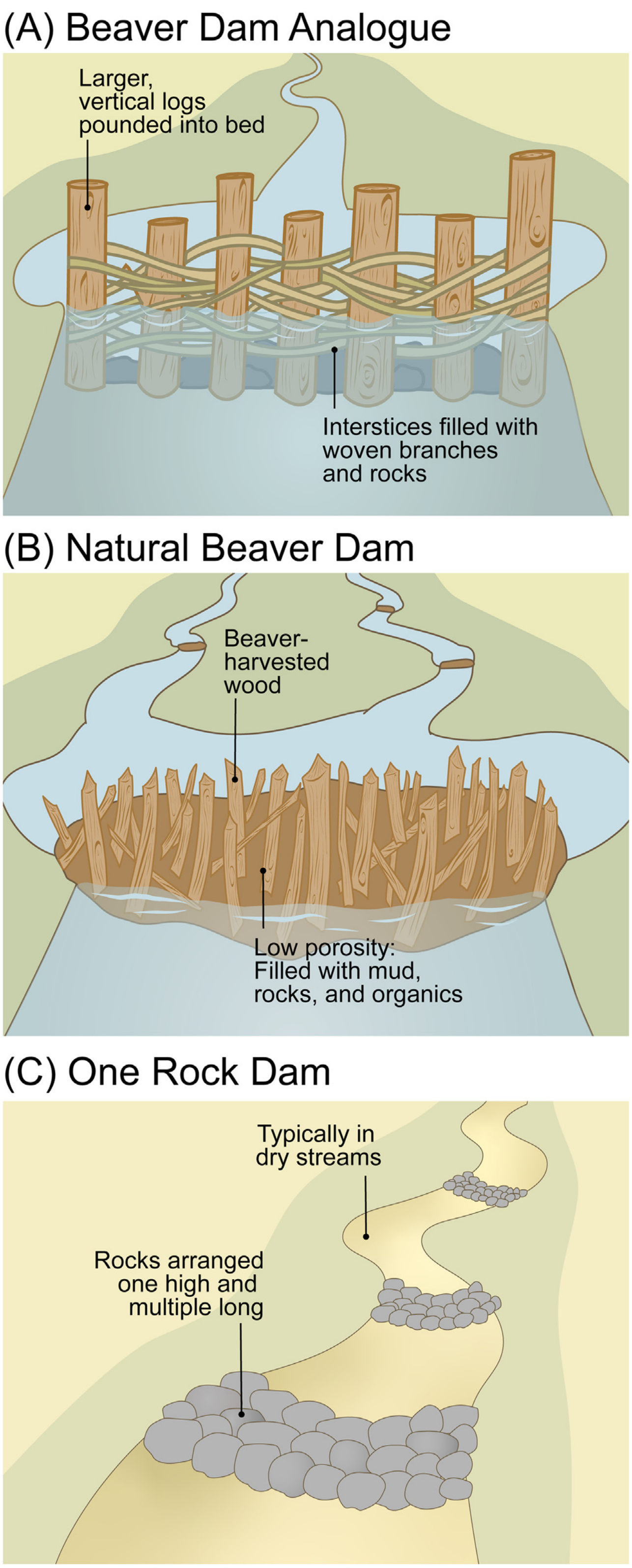

Figure 2. Common low-tech process-based restoration structures in use across the western U.S.: (A) beaver dam analogues, which are artificial structures meant to mimic the impact of natural beaver dams, (B) natural beaver dams, which are low-porosity, natural structures built by beaver, and (C) one rock dams, which are artificial structures built by arranging rocks one rock high and multiple long. Design by J. Scamardo.

and nitrogen, and water and sediment storage, which can support habitat diversity for native flora and fauna across the river corridor (Butler and Malanson, 2005; Pollock et al., 2007; Burchsted et al., 2010; Morra et al. 2023). Moreover, increasing riparian vegetation health can foster positive feedback with instream recovery, as vegetated areas can mitigate erosion, regulate flooding events (Tabacchi et al., 2000; Staddon et al., 2001), and moderate surface water temperature and evaporation by blocking incoming solar radiation (Dugdale et al., 2018).

Nash et al. (2021) detailed the processes that must occur for LTPBR projects to achieve these expected outcomes, including that structures must be built and maintained. However, even if a project achieves a desired outcome, considerable variability in the magnitude of change following LTPBR has been reported in the literature. Factors such as time since restoration (e.g., Ecke et al., 2017), the number of structures installed (e.g., Nash et al., 2021), and local precipitation or climate at the project site (e.g., Scamardo and Wohl, 2020; Dittbrenner et al., 2022) are all thought to drive variability in the magnitude of change following LTPBR, but quantitative comparisons across projects have rarely been made.

Beyond environmental factors, rangeland streams are social-ecological systems, meaning that the use and outcomes of LTPBR are additionally dependent on multiple social dimensions (Dunham et al., 2018; Charnley et al., 2020). Growth of the stream restoration industry was initially driven by federal legislation, such as the Clean Water Act and Endangered Species Act in the U.S., which can hold communities liable for maintaining water quality standards and habitat in navigable waters (BenDor et al., 2015). However, choice of using LTPBR across the western U.S. is largely dependent on landowner interest and commitment (Charnley et al., 2020), which studies have suggested may be shaped and informed by LTPBR practitioners (e.g., Norman et al., 2020). Concerns over water rights, particularly in water-scarce environments, may (Jordan and Fairfax, 2022; Pennock et al., 2022) or may not (Pilliod et al., 2018; Charnley et al., 2020) be a barrier to LTPBR implementation. Water law in the western U.S. is based on the prior appropriation doctrine that centers on diverting water from a watercourse and applying it to a state-defined beneficial use (Wiel, 1911; Sea Grant Law Center, 2002), which historically excluded instream and environmental uses that would include practices such as LTPBR (Trelease, 1957). Prior appropriation poses two potential barriers to LTPBR in the western U.S.: the “use it or lose it” principle which dictates that water users may lose their water right if not applied to a beneficial use, and the “no injury” rule which states that a water rights holder cannot change the purpose of water use on a water right if the change adversely affects downstream water users. Changing beneficial use definitions and determinations of ‘no injury’ could provide future opportunities to use water rights for instream purposes (such as LTPBR implementation) without risking the loss of those rights.

Further research into the physical factors and social dimensions that influence LTPBR use and effectiveness is needed to improve our understanding of LTPBR as a tool for building resilience to future change and disturbance. To further address the unknowns and potential barriers to LTPBR in water-limited rangelands across the western U.S., we pose two questions: 1) How do physical characteristics of LTPBR projects (including structure type, number, and local setting) influence the magnitude of physical changes following LTPBR?; and 2) How are social dimensions related to practitioner attitudes and water law impacting LTPBR implementation and success? We focus on three types of LTPBR, which are expected to restore similar processes at similar spatial scales: natural beaver dams, BDAs, and ORDs (Fig. 2). Studies of change following beaver dam, BDA, and ORD construction in rangeland streams in the western U.S have increased in the last decade, and particularly in the past five years, allowing for a quantitative, cross-project compila-

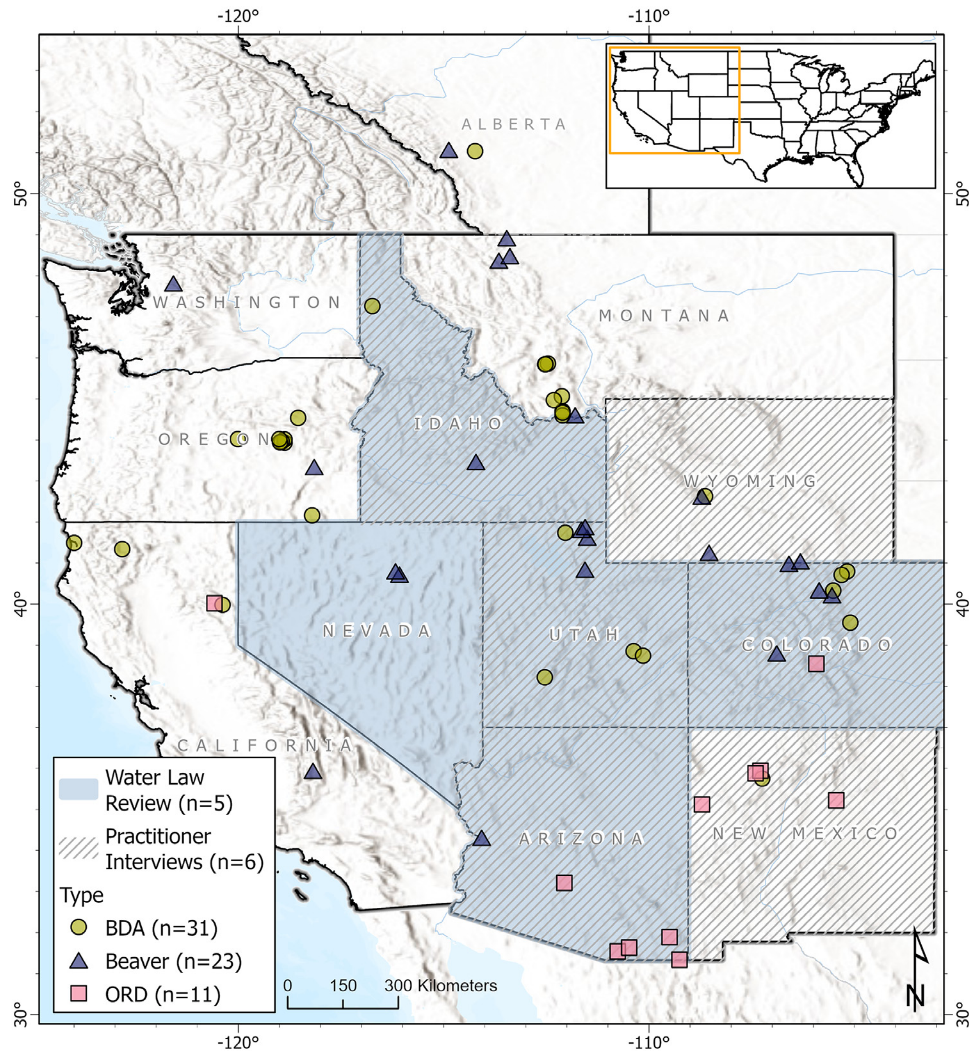

Figure 3. Location within western North America for the water law review (blue shading), interviews (hatching), and restoration projects (symbols by type).

tion and comparison. We pair this analysis with a review of current legal beneficial use definitions and practitioner attitudes towards LTPBR to further identify and discuss the potential for using LTPBR as a future resiliency tool in water-limited environments.

Methods

Study area

We focused on rangeland stream networks in western North America that flowed through arid to semi-arid shrubland environments with potentially forested subalpine headwater catchments (Fig. 3). The majority of shrublands in the western and southwestern U.S. can be classified as cool, semi-desert, per the U.S. National Vegetation Classification (USNVC, 2022). These are typically found at mid-latitudes (35–55°N) and mid-elevations (500–2,500 m) and are dominated by moderate to dense shrub cover with underlying or patchy grasses. Higher elevations in the montane and subalpine zones within these regions will often be temperate shrublands, and projects located in these zones were additionally considered.

Data collection and analysis for LTPBR project outcomes

Published studies were found using a keyword search in Web of Science and Google Scholar in April 2022, including terms related to restoration type ("BDA", "beaver mimicry", "beaver", "one rock dam", "process-based"), location ("Southwest", "West", and specific state names), and outcome ("water storage", "sediment storage", "temperature", "outcome"). The original search returned fewer than 30 studies, resulting in an expansion of the search to include well-known LTPBR projects and literature cited in the previously identified papers. In total, 62 papers were identified - including peer-reviewed articles, white papers, and academic theses - on 65 restoration projects from across western North America (Fig. 3). We focused on studies that provided a quantitative assessment of change at either two points in time (i.e., before and after a restoration project) or two points in space (i.e., restored and control). Given these criteria and the lack of common keywords in the literature, the studies used here may not represent all published literature on monitored instream LTPBR outcomes across the study area.

Metrics of hydrologic, geomorphic, and biotic change post-restoration were extracted from each study. Common hydrologic metrics included changes in volumetric water storage (m^3), groundwater depth (m), water stage (m), discharge ($m^3 s^{-1}$ or cms), and stream temperature (°C); common geomorphic metrics included changes in volumetric sediment storage (m^3) and vertical sediment depth (m); and a common biotic metric was change to vegetation greenness using the normalized difference vegetation index (NDVI, %) (Table 1). When available, raw values (for

Table 1
Metrics for monitored projects, with standard SI units where applicable. Metrics with units of na (not applicable) are unitless.

Characteristic	Metric (units)
Sediment storage	Sediment volume (m^3) Sediment depth (m) Sediment load (% change)
Surface water storage	Water volume (m^3) Discharge (cms) Stage (m) Runoff ratio (*na*) Wetted area (m^2, % change)
Groundwater storage	Depth to groundwater (m) Soil moisture (m^3/m^3)
Temperature	Water temperature (°C) Soil temperature (°C)
Vegetation	NDVI (*na*) NDII (*na*) Species Diversity (*na*)

before-after or restored-control) were extracted from each study. However, many studies only reported project means or medians and, in some cases, only the comparative changes (before-after or restored-control) were reported. Where comparative values were not provided, they were calculated by differencing the mean restored value by the mean non-restored (either before or control) value. Given that not all studies have an associated standard deviation (where means or magnitudes of change were reported), standard effect sizes could not be calculated. Instead, the magnitude of each outcome metric (i.e., absolute change) from each study was reported and compared.

Project characteristics were compiled for each site, including restoration type (BDA, Beaver, ORD), time (in years) since restoration, and number of structures implemented. Standard metrics to describe the location and climate of each project site were also recorded, namely elevation, latitude, drainage area (in km^2), and mean annual precipitation (in mm). Mean annual precipitation was not consistently reported in the published literature, so values were derived from PRISM datasets, which provide annual precipitation averages calculated over a 30-year window from 1971 to 2000 for the conterminous U.S. (Daly et al., 2008). PRISM data were accessed via the U.S. Geological Survey StreamStats web application (https://streamstats.usgs.gov). Where available, precipitation values reported at a study site were compared to the derived PRISM values (Fig. S1; Table S1); these had a strong linear correlation (slope = 1.009) with a slight (~4 cm) positive bias in the PRISM data.

The correlation and sensitivity of restoration outcomes to restoration project characteristics (e.g., structure type and number) and climate (e.g., project latitude and mean annual precipitation) were assessed using generalized additive linear models Bates et al. (2014). Continuous variables (i.e., number of structures and latitude) that varied significantly in magnitude compared to response variables were rescaled using the `scale()` function in R, so that their effect on the restoration characteristic (e.g., sediment storage) could be interpreted on the same magnitude as the response. All statistical models were developed in R version 3.0.1 R Team (2021). An alpha = 0.05 was used to determine significance of all statistical tests.

Review of water law relevant to instream restoration

We reviewed relevant water law by examining existing legal and policy papers, government documents, and academic literature on water law and instream flows for five western U.S. states (Colorado, Utah, Idaho, Nevada, and Arizona) (Adler, 2020; Craig, 2020). We also considered state-specific statutes related to instream flows, definitions of beneficial use, the no injury rule, and other statutory provisions to determine whether states legislatively promote the use of instream flows. We determined which of six considerations for allowing instream flow rights as set forth by Boyd (2003) had been implemented in each state: 1) an express finding by the state legislature that functioning riparian ecosystems are economically indispensable, 2) the legislature or courts determine water use for ecological preservation is deemed a "beneficial use," 3) water rights do not require a diversion, 4) conservation measures allow continued ownership of nondiverted instream flow, 5) individuals and organizations can hold instream water rights, and 6) watershed-based management plans encourage the cooperation of all stakeholders. Additionally, we searched for state legislation that identifies whether LTPBR has a presumed "no injury" on water rights holders.

Interviews with practitioners

We conducted interviews with stream restoration practitioners in the western U.S. to understand their professional perceptions and experiences of LTPBR. The interviewees were chosen using purposeful sampling to identify professionals (including restoration contractors, wildlife agency staff, watershed scientists, non-profit conservation organization staff, and water policy experts) relevant to the study (Patton, 2015). This project did not require Institutional Review Board oversight based on definitions of human subjects research. However, we followed accepted best-practices in informing participants about the purpose of the research, their rights to decline participation, and their rights to remain anonymous. We organized 13 semi-structured interviews using a set of 20 questions informed by the reviews of existing LTPBR, water law, and climate adaptation literature. All interviews were recorded and transcribed, so that collaborative descriptive coding could be used to identify common themes (Saldaña, 2016). Codes included the ecological, social, and climate adaptation outcomes of LTPBR, implementation challenges, and practitioner recommendations.

Results

Hydrologic, geomorphic, and biotic outcomes of PBR

The 65 LTPBR projects identified in the literature included 31 BDA sites, 23 beaver relocations sites, and 11 ORD sites. Colonization of BDAs by beavers was explicitly mentioned at one project site (Bouwes et al., 2016); otherwise, BDA projects were assumed to not be impacted by beaver activity. The majority (77%) of the projects were situated in perennial streams. Fifteen projects were in non-perennial streams, most (n = 9) of which used ORDs. The concept of watershed-scale restoration combining ORDs in non-perennial streams with wooden structures in downstream perennial rivers was mentioned in three studies (Berry, 2021; Norman, 2020; Norman et al., 2022). Structure stability was not explicitly noted in most studies, but six studies (9% of projects) reported structure failure during the study period. The majority (94%) of studies were based on field observations and did not include pre-restoration measurements (55%). Despite potential differences that might arise due to differences in monitoring design, we compared all available values because of the limited sample size for each metric (Table 2).

A total of 33 projects (51% of all projects) monitored sediment retention in some manner, 41 (63%) monitored water storage, 13 (20%) monitored stream temperature, and 18 (28%) monitored changes in vegetation greenness along the restored stream reach (Table 1 and 2). Of the projects that monitored each characteristic, 91% (30 projects) found net sediment deposition, 93% (38

Table 2
Median recorded responses of restoration by metric. Responses were calculated by comparing before and after restoration or restored and control reaches.

Change metric	Average response [Standard deviation]	Number of projects
Sediment volume	+314 m^3 [642 m^3]	18
Sediment depth	+0.7 m [0.9 m]	8
Water volume	+1046 m^3 [2126 m^3]	21
Downstream discharge	-0.007 m^3/s [0.14 m^3/s]	8
Depth to groundwater	-0.3 m [0.2 m]	16
Stream stage	+0.6 m [0.7 m]	23
Stream temperature	-0.32 °C [1.3 °C]	13
NDVI	+0.14 [0.11]	19

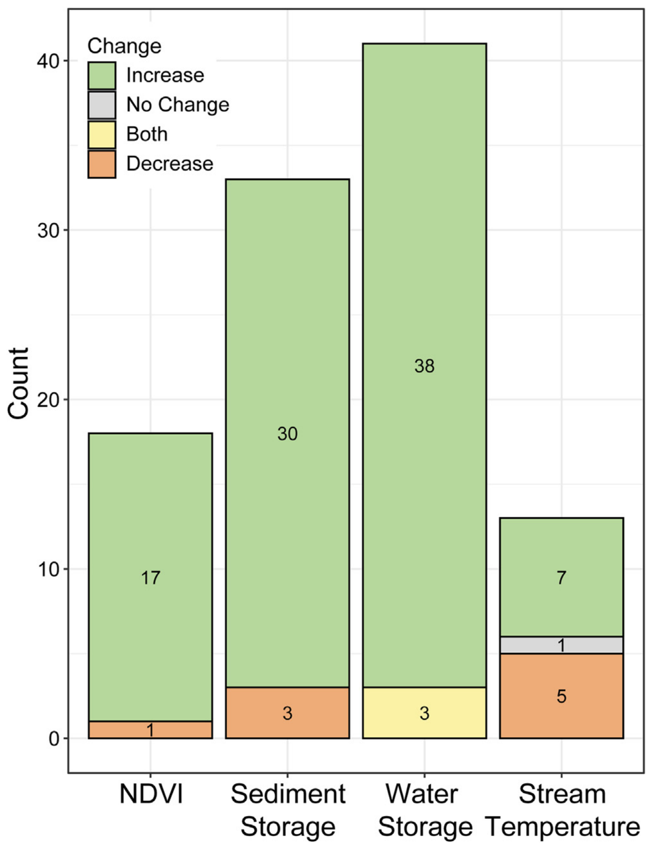

Figure 4. Number of projects that found a net increase, decrease, or no change following LTPBR implementation. Certain projects monitoring water storage found both a net increase or a net decrease, depending on the attribute of water storage measured (see Table 1).

projects) found at least a temporary increase in water storage, 38% (5 projects) found a decrease in stream temperature, and 94% (17 projects) found an increase in vegetation greenness (Fig. 4; Supplemental Table S2). Average magnitudes of LTPBR outcomes following restoration across all 65 projects for metrics with more than three observations can be found in Table 2.

Magnitudes of response to LTPBR were correlated to mean annual precipitation, time since restoration, project latitude, and structure type. Projects in relatively wetter climates (higher precipitation) experienced increased downstream flow ($\beta_{\text{discharge}} = 0.20 \pm 0.08$, $p = 0.04$) post-restoration. Changes in downstream flow did not vary significantly with time since restoration (Fig. 5). Differences with seasonality (i.e., baseflow vs peak flow) were difficult to assess quantitatively, but five studies reported data collected during peak flows (Andersen et al. 2011; Briggs et al. 2012; Norman and Niraula 2016; Munir and Westbrook, 2021; Tosline et al., 2021), two studies were conducted at base flows (Wegener et al. 2017; Shahverdian et al. 2018), and one study was conducted at both peak and base flows (Majerova et al. 2015). Of these studies, three reported a decrease in downstream discharge or runoff (Andersen et al., 2011; Briggs et al., 2012; Tosline et al., 2020), four projects reported an increase in downstream discharge (Majerova et al., 2015; Norman and Niraula, 2016; Wegener et al., 2017; Shahverdian et al., 2018), and one paper reported both increases and decreases in downstream discharge dependent on the number of installed structures (Munir and Westbrook, 2021). Twelve percent of studies mentioned that restoration was associated with measured or anecdotally higher base flows, and 14% of studies reported attenuated peak flows.

Increasing time since restoration led to larger volumes of sediment storage ($\beta_{\text{sediment}} = 41.05 \pm 16.36$, $p = 0.02$) and larger decreases in stream temperature ($\beta_{\text{temperature}} = -0.56 \pm 0.21$, $p = 0.03$). Stream temperature additionally correlated with project latitude, such that projects at higher latitudes experienced stream cooling (maximum cooling of -3.3°C at 44.54°N) and projects at lower latitudes experienced stream warming (maximum warming of +1.3°C at 39.9 °N) ($\beta_{\text{temperature}} = -0.16 \pm 0.06$, $p = 0.04$).

Beaver dams stored significantly more sediment than BDAs or ORDs ($p = 0.03$). Although the sample size is limited, our results supported findings from available studies suggesting that ORDs store significantly less water than beaver dams or BDAs ($p = 0.03$). It is worth noting that restoration type did not influence outcomes related to vegetation greenness (Fig. 5), but that the largest post-restoration NDVI change was associated with natural beaver dams. Additionally, although 98% of the projects monitoring water storage reported increases, changes in depth to groundwater levels did not show any trends across projects. No metrics significantly correlated to the number of structures built at a site. Beyond quantitative analyses, findings from individual projects and papers lead to further discussion on stream resilience to a warmer climate and changing water diversion, including resilience to declining streamflow and higher temperatures.

Review of water law relevant to instream restoration

Acknowledging that over-appropriated rivers and streams were causing damage to riparian ecosystems, legislatures and courts have sought to protect and restore riparian habitat by establishing a right to “instream flows” (Boyd, 2003). A right to “instream flows”, effectively creates a water right that allows water to be considered “used” even if left in place to pass through a water course for environmental purposes. Arizona, Colorado, Idaho, and Utah have created statutory schemes to administer instream flow programs, while Nevada’s instream flow administration is the result of a Nevada Supreme Court decision (Table 3). Of the five states we reviewed, only Colorado and Utah include specific statutory language expressing the protection of the environment as a beneficial use (Table 2). Colorado law creates a beneficial use for protecting “the natural environment” (Co. Rev. Stat. § 37-92-101, 2022), and Utah considers “the reasonable preservation or enhancement of the natural stream environment” to be beneficial (H.B. 33-272, Gen. Sess. Utah 2023). In contrast, the remaining

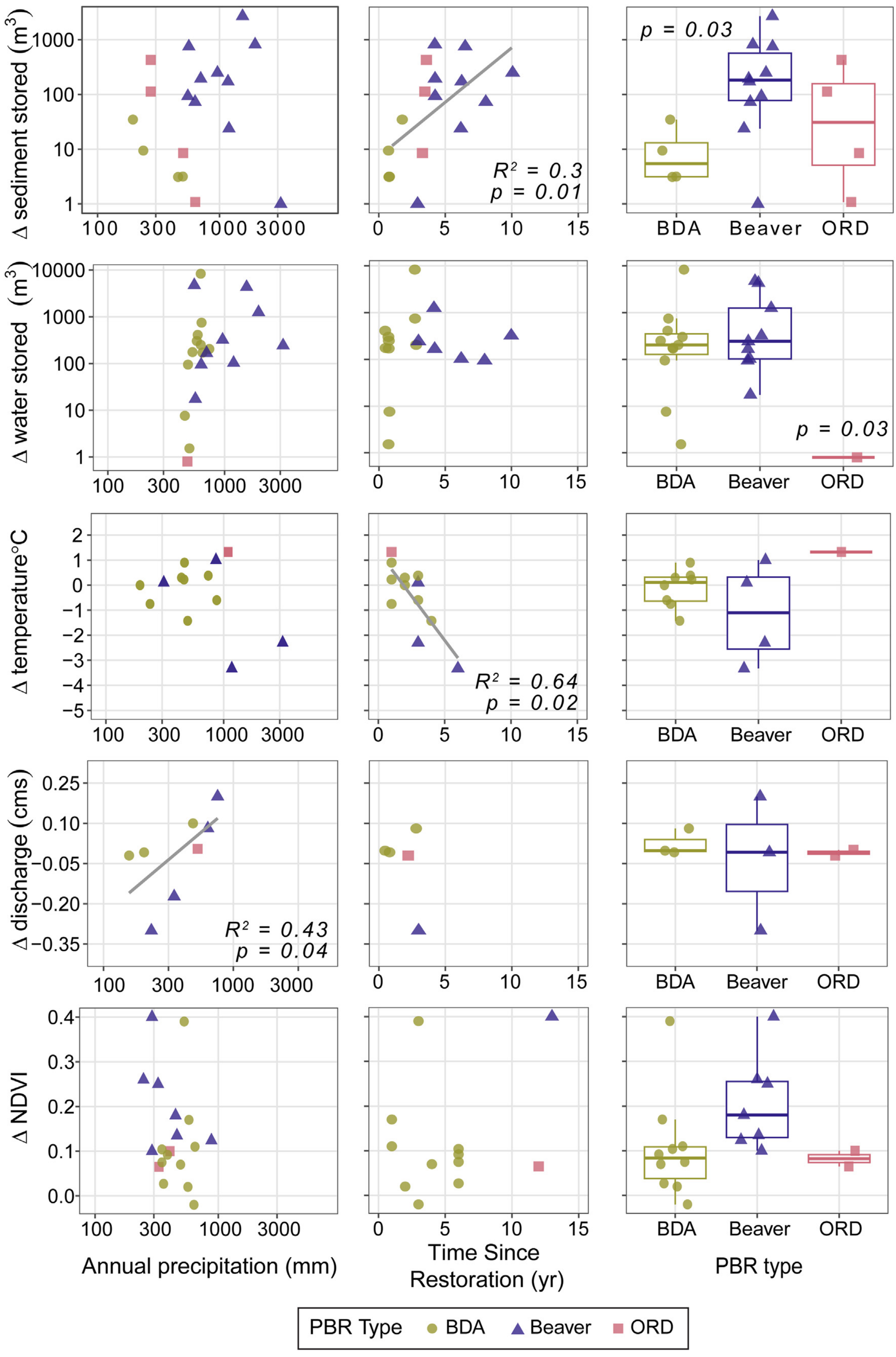

Figure 5. Modeled trends for common restoration outcomes: A) change in water temperature (°C), B) change in stream discharge (cms), C) change in water storage per structure (log transformed) (m^3), D) change in sediment stored per structure (m^3) and E) change in NDVI (%) based on average annual precipitation (mm) for each study area (log transformed), and the LTPBR type: BDA, beavers, or ORD. Yellow circles represent BDA projects, purple triangles represent beaver projects, and pink squares represent ORD projects. Solid lines represent statistically significant trends based on general additive linear models (glm), r^2 represents the variance explained by the entire glm, and p-values for LTPBR type are displayed when $p < 0.05$.

Table 3
Instream flow considerations (as defined by Boyd, 2003) by state as of October 2023.

Consideration	State				
	Arizona	Colorado	Idaho	Nevada	Utah
Statutory language expressing indispensable nature of riparian ecosystems	Yes	Yes	Yes	Partial, for wildlife and wildfire mitigation	Yes
Ecological preservation is a "Beneficial Use"	Not Defined, but appropriation for wildlife allowed	Yes	Indirectly	Not Defined, but recognized by State Engineer	Yes
Diversion from stream required by water right	No	No	Partial, instream flows allowed for stock watering	No	No
Maintain ownership of excess, instream flow	Yes	Yes, water loan program	Yes	No	Yes, water banking program
Private individuals and organizations allowed to hold instream rights	Yes	No, state agencies only	No, state agencies only	Yes	No, state agencies only
Promotion of cooperative, watershed-based management plans	Yes	Yes	Yes	Yes	Yes

states allow for the beneficial use of instream flows indirectly by extending beneficial use to include the protection of fish and wildlife habitat, as well as for recreational purposes. Although not expressly allowing environmental purposes as a beneficial use, these states have ensured that a mechanism exists where water can legally remain in the watercourse, thereby indirectly allowing water to be used for environmental purposes. Idaho is the only state that still requires the diversion of water to obtain a water right; however, the State has provided an exception to the beneficial use standard, which includes instream flows (Boyd, 2003). Arizona, Colorado, Nevada, and Utah allow for water rights to be acquired for the purpose of instream flow.

Regarding the "use it or lose it" precedent which discourages current rights holders to temporarily reduce water diversions, Arizona (Ariz. Rev. Stat. § 45-189.01) and Idaho (Idaho Rev. Stat. § 42-250) include language to allow water rights to be retained on conserved (i.e., unused) water. Colorado established an instream flow loan program allowing water rights holders to reduce their water use for 5 out of 10 years without losing their water right (Co. Rev. Stat. §37-83-105). Nevada does not allow for any exception for conserved water, further limiting instream flow protection options. In 2022, Utah passed and signed into law a bill, HB33, allowing farmers to leave water in the channel without losing their allotted rights by changing the definition of "beneficial use" to include instream flows that benefit wildlife. In all states, government agencies such as the Utah Division of Wildlife Resources, Utah Division of State Parks, Division of Forestry, Fire, and State Land, and Colorado Water Conservation Board can hold instream flow rights (CWCB, 2005; Utah Code Annotated §73-3-30). Moreover, in Colorado and Utah, individuals can donate, sell, or transfer water rights to government agencies for instream use. Only in Arizona and Nevada are non-government agencies also able to obtain and maintain water rights for instream flow (CWCB, 2005). All reviewed states have active statewide Water Management Plans with public comment periods. These Water Management plans are often the result of cooperative agreements based on the execution of plans by local watershed groups and stakeholders like the WaterSMART Cooperative Watershed Management Program which is overseen by the U.S. Bureau of Reclamation (https://www.usbr.gov/watersmart/cwmp/index.html).

Water rights can be used or transferred to instream flow projects if they constitute "no injury" to other water rights holders (Szeptycki et al., 2015). For the case of LTPBR projects that may impound water, an assumption of no injury is typically made on a case-by-case basis approved by the state engineer or similar official via a permitting process, as is the case in Utah (UDNR, 2018), Idaho (IDWR, 2019), and Wyoming (Wyoming State Engineer's Office, 2018). Projects that are presumed to have no injury to rights holders may not need a water right to proceed. Recent legislature in Colorado - SB 23-270 - deemed certain stream restoration practices as having no injury, including erosion control structures in ephemeral streams and post-wildfire and post-flood recovery projects.

Interviews with stream restoration practitioners

The 13 interviewed practitioners have diverse backgrounds in the implementation, management, and research of stream restoration. They reported professional experience in the non-profit sector ($n = 7$), private sector ($n = 5$), water policy sector ($n = 2$), research ($n = 2$), and state wildlife agencies ($n = 1$). Practitioners who work in multiple sectors were counted in multiple categories. The majority ($n = 10$) of the interviewees are directly involved in a wide variety of restoration projects, including beaver reintroductions and the installation of BDAs and ORDs. The other three had direct experience in water law, policy, and multi-stakeholder wa-

Table 4
Coded interview results. Codes represent perceived benefits, challenges, and recommendations categorized into common themes.

Code	Theme	Number of interviews that mention theme
Ecological benefits	• Increase habitat for native plants, wildlife, and livestock.	12
	• Regenerate riparian vegetation.	11
	• Create pools to store sediments and improve water quality.	11
	• Restore native fish populations.	10
	• Enable beavers to resume their role as ecological engineers.	10
Social benefits	• Restoration projects connect people with watersheds and ecosystems.	13
	• Partnerships formed in the restoration process support further collaborations.	13
	• Successful demonstration sites encourage more restoration projects.	12
	• Recreation opportunities at restoration sites.	3
Climate adaptation benefits	• Mitigate the impacts of drought.	13
	• Reduce flood risk.	9
	• Improve wildlife habitat connectivity and quality.	10
	• Provide wildfire refuge.	4
Challenges	• Floodplains of streams and rivers are not well protected from development.	13
	• Lack of stream gauges and common indicators for post-restoration monitoring.	10
	• Lack of funding support for post-restoration monitoring and maintenance.	10
	• Variation in local attitudes and perceptions about working with beavers.	10
	• Obtaining permits from federal agencies can be slow.	3
	• Water law and water rights are ongoing challenges to implementation of projects.	2
Recommendations	• Increase local stakeholder engagement and relationship building.	13
	• Create demonstration sites for stream and restoration storytelling to communicate ecological, social, and climate adaptation benefits.	11
	• Increase monitoring and long-term measurements	10
	• Engage new water law and policy at the state, local, and agency level to ensure instream flows.	3

tershed collaborations. Although the sample is not representative of all restoration practitioners, the interviews provided additional, qualitative context for the findings from meta-analysis and the legal review.

The majority of interviewees mentioned themes of observed ecological benefits at restoration sites for habitat ($n = 12$), riparian vegetation ($n = 11$), and sediment and surface water storage ($n = 11$) (Table 4). All interviewees ($n = 13$) mentioned that in-stream LTPBR mitigated against drought by prolonging streamflow and turning intermittent streams perennial. Interviewees stated common challenges to restoration activities, such as building on floodplains ($n = 13$) and insufficient resources for monitoring ($n = 10$).

All interviewees identified the need for stream restoration practitioners to nurture ongoing collaborative partnerships with local stakeholders (Table 3). Potential LTPBR projects exist across a range of ecological contexts (mountains, deserts, grasslands), regulatory frameworks (federal, state, tribal, and private land), and local attitudes (supportive versus unsupportive of restoration). Organizing local and regional stakeholder collaborations was recommended to design tailored LTPBR projects that meet local needs and conditions. Interviewees also reported that, in their experience, successful restoration collaborations enable future restoration projects. The importance of ongoing collaboration was also highlighted by 10 of the interviews which noted the need for continued monitoring and maintenance of LTPBR sites.

Discussion

Quantifiable trends in LTPBR outcomes across the western U.S

The majority (>80%) of synthesized LTPBR projects were storing sediment and water and increasing river corridor greenness as expected (*sensu* Nash et al., 2021), but the magnitude of change was site specific, depending on location and design choices (Fig 5). Still, our synthesis generally supports conceptual hypotheses on the hydrologic, geomorphic, and biotic impact of LTPBR (e.g., Pollock et al., 2014; Fig. 1), thus joining previous syntheses by further confirming that trends seen at individual study sites are common across western North America (e.g., Jordan and Farifax, 2022; Norman et al., 2022; Skidmore and Wheaton, 2022; Corday, 2024).

Despite previous studies suggesting that the magnitude of LTPBR outcomes might be driven by local climate (i.e., mean annual precipitation; Scamardo and Wohl, 2020, Dittbrenner et al., 2022) and subsequent sediment availability (*sensu* Langbein and Schumm, 1958), few metrics varied significantly with changing water availability (Fig. 5). As Nash et al. (2021) suggested, water and sediment storage occurred irrespective of project location, with similar magnitudes of storage observed across a wide precipitation gradient. Changes in vegetation greenness (NDVI) were similarly not impacted by mean annual precipitation, further confirming Silverman et al. (2018) who found a decoupling between greennes.s and water availability during drought at LTPBR sites. Only changes in discharge significantly varied with precipitation, where wetter environments exhibited increases in downstream discharge and drier environments exhibited decreases (Fig. 5). In general, LTPBR restoration projects have previously been perceived as sponges that fill up during high flows and in the shorter-term following restoration, and then release higher discharge at base flows and in the longer term (*sensu* Pollock et al, 2014; Wohl, 2021). The relationship between discharge changes and precipitation could suggest that water limited environments may not receive the same benefits to downstream discharge (i.e., enhanced baseflow) as projects in wetter environments, potentially due to high water storage capacity (e.g., low water tables) in arid environments. Alternatively, variations in discharge changes could be a factor of the season (i.e., high or low flow) during which measurements were made across studies; projects that reported decreases in downstream discharge (Andersen et al. 2011; Briggs et al. 2012; Munir and Westbrook, 2021; Tosline et al., 2020) reported discharge at peak flows (either early summer or during flood stages). Projects that reported an increase in downstream discharge monitored both peak and base flows (Majerova et al., 2015) or primarily base flows (either non-flood events or fall/winter; ;Wegener et al. 2017; Shahverdian et al. 2018). Qualitatively, discharge changes could be reflective of increased baseflow (positive changes) and decreased peak flows (negative changes) (Fig. 5), and the relationship with precipitation could be spurious. Overall, interpretations of discharge changes following LTPBR should also be taken cautiously; changes are small

(± 0.5 cms) which could be within the range of error for discharge measurements through a restored reach (Nash et al., 2019). Future monitoring studies, particularly those that account for seasonality, are still needed to elucidate the influence of LTPBR on streamflow.

Design choices and time since implementation had stronger correlations to LTPBR outcomes than local precipitation. Changes in sediment volumes had a strong positive relationship with time since restoration, likely indicating the continual accumulation of sediment following LTPBR implementation (a trend also found by Butler and Malanson (1995) for natural beaver ponds and Bouwes et al. (2016) for BDAs). By comparing across space as a proxy for time, increases in sediment volumes did not appear to level off with time (Fig. 5), which may be expected as ponds fill and reach a limit of storage (e.g., Nash et al., 2021). A lack of sediment storage limit may be due to structure type: beaver dams stored significantly more sediment than BDAs or ORDs and accounted for all the highest reported changes in sediment volumes (Fig. 5). Given that intact beaver dams are continually maintained, ever increasing sediment volumes may reflect continual expansion of beaver dams over time, although explicit mention of changes to beaver dam structures were often not recorded in the literature. Unlike sediment, increasing time since restoration did not have a significant impact on water storage, and BDAs and beaver dams were found to comparably increase water storage volumes (Fig. 5). Past studies found that increased water storage volumes buffered daily temperature extrema, thus improving habitat for a range of aquatic biota (Weber et al., 2017; Dittbrenner et al., 2022). LTPBR was found to have a greater benefit (i.e., greater decreases) to stream temperature with increasing time since implementation despite a lack of trend in water storage volumes (Fig. 5). Beyond the direct influence of water storage, decreased stream temperatures could be driven by increasing shade from growing large, woody vegetation supported by greater water availability near LTPBR projects, as suggested by Pollock et al. (2007) and generally higher NDVI at LTPBR sites (Fig 5). Stream temperature changes could also be indicative of increasing inputs from rising water tables at LTPBR projects (Table 2).

Overall, the finding that structure type and time following restoration may influence LTPBR outcomes more than local annual precipitation emphasizes that key design choices could be made to encourage expected outcomes regardless of shifting water availability due to climate change. Additionally, similarities between structures suggest flexibility in the type of LTPBR implemented. Natural beaver dams may be better suited for storing excess sediment in the river network, but artificial structures (namely, BDAs) can elicit similar water storage, temperature, discharge, and vegetation responses (Fig. 5). Consistent responses across LTPBR types could encourage the use of artificial structures in streams where suitability for natural structures is low (e.g., Wohl, 2021; Scamardo et al., 2022).

Changing water law and perceptions of LTPBR

Despite a consistently acknowledged lack of funding for post-restoration monitoring, most interviewed practitioners recognized and discussed the perceived ecological benefits of LTPBR (Table 4), suggesting that a lack of scientific evidence may not be the primary social barrier to LTPBR implementation for LTPBR practitioners. Instead, practitioners commonly discussed variations in local attitudes towards LTPBR as being a barrier to future implementation, which is consistent with recent evidence from restoration projects in Oregon, Nevada, and California (Charnley et al., 2020). Charnley et al. (2020) also found that water rights were of limited concern at LTPBR sites, likely because there had been no perceived injury to downstream water users. Although only included in a limited subset of restoration professionals across the western U.S., attitudes towards water rights and LTPBR were reflected in our practitioner interviews, where water rights were only mentioned as an issue for LTPBR twice (Table 4). Despite limited concern, others have suggested that the use of water rights for instream flow could be critical for the long-term success of LTPBR in the future (e.g., Pennock et al., 2022).

Over the past two decades, the majority of states in the intermountain western U.S. have adopted instream flows as a beneficial use (Table 3). Although instream flow programs exist in many states, their use and effectiveness are still questioned. Some legal commentators are concerned that private entities are limited in their choice to conserve because instream flow rights are often only granted to government entities (Smith, 2019). Certain aspects of instream flow rights – low seniority, legislative qualifications, or poor enforcement – have made them seem weaker or subordinate to diversionary rights, leaving opportunities for further legal debate when it comes to using instream rights for LTPBR projects that may pond water. Still, expanded beneficial use definitions are a first step towards utilizing water rights to allow LTPBR projects to pond and store water, which was a commonly reported outcome at LTPBR projects in the western U.S. (Fig 5, Table 2).

In many states, obtaining a water right is not necessary for LTPBR implementation if projects meet "no injury" presumptions (e.g., UDNR, 2018). In Colorado, SB 23-270 (passed in June 2023) acknowledged the importance of stream restoration and declared that "minor stream restoration activities" were non-injurious to downstream water rights holders. Under the bill, "minor stream restoration activities," does not cover all forms of LTPBR (Romero-Heaney, 2023), but does potentially include ORDs in ephemeral streams as well as LTPBR projects used in post-wildfire or post-flood recovery projects. Although not inclusive of all LTPBR, legislation like SB 23-270 underscore the timely interest in determining rules and regulations for LTPBR specifically (Romero-Heaney, 2023)

LTPBR projects that do not meet "no injury" definitions determined at the state level may be required to obtain a water right, in which case expanded beneficial use definitions would be critical to project implementation. Novel economic incentives, like water banking, could help meet the legal needs of larger LTPBR projects (Table 4). Water banks allow conservation organizations and natural resource agencies to acquire permanent, temporary, and split-season water rights, aggregating them to produce sufficient water to support instream flows (*sensu* Green and O'Connor, 2007). Water banking applications have been implemented throughout the western U.S., such as the Price River Collaboration, where reservoir releases provided through partner water rights on the Price River (Utah) are used to provide ecological flows benefitting endangered fish during low flow periods (The Nature Conservancy, 2020). Water banking for instream flows could be combined with ongoing LTPBR, such as beaver reintroduction, to further create and protect instream habitat. A combination of flexible water management tools and LTPBR techniques is just one example of how law and restoration practice can cooperate to create watersheds resilient to a changing climate in the western U.S. and other, similar rangelands.

Implications for future use and monitoring of LTPBR

Scientists are increasingly calling for the use of LTPBR as a climate adaptation tool (Jordan and Fairfax, 2022; Pennock et al., 2022; Skidmore and Wheaton, 2022; Norman et al., 2022), which was additionally mirrored in responses from practitioners (Table 4). All interviewees held the impression that LTPBR could help mitigate the impacts of drought and declining water availability across the western U.S. Results from LTPBR monitoring suggest that LTPBR could, depending on time and precipitation, decrease warming stream temperatures, supplement declining baseflows, temporarily store limited water and excess sediment, and support riparian habitat (Fig. 5), such that water-stressed river corridors could regain a number of key functions following LTPBR implementation.

Certain aspects of LTPBR, such as increased greenness and water storage, may be especially important for increasing watershed recovery and resilience to climate-driven disturbances such as wildfire and drought (Fairfax and Whittle, 2020; Skidmore and Wheaton, 2022). Temporary storage of surface water and groundwater, which was found at 91% of study sites (e.g., Karran et al., 2018; Wilson and Norman, 2018; Silverman et al., 2019 from review), can support healthy river corridor vegetation during periods of low water availability and reduce susceptibility to fire. LTPBR implemented immediately following fire can help river corridors recover by settling turbid water and storing high sediment loads associated with rapid post-fire surface water runoff to downstream ecosystems (Fairfax and Whittle, 2020; Wohl et al., 2022). Accordingly, the use of LTPBR to mitigate wildfire impacts is increasing, which was mentioned in 30% of practitioner interviews (Table 4).

Although post-project monitoring of LTPBR in the western U.S. has increased over the past decade, thus leading to our attempt at quantitative, cross-project comparisons across the region, more monitoring is needed to further elucidate the relationships between LTPBR outcomes and project location and design. This call for expanded monitoring is not new (e.g., Pilliod et al., 2018), but our analysis further highlights the need for additional studies on water temperature and discharge, which show substantial variability (both positive and negative outcomes) following restoration. Research that fills geographic gaps or assesses LTPBR project performance under climatic events such as severe droughts and floods are still limited, and additional long-term monitoring of LTPBR projects over the coming decades is needed to further understand the potential to use restoration to adapt to changing climate. Additionally, the majority of studies are still reporting on differences between restored and control reaches, instead of pre- and post-restoration (an issue raised by Lautz et al. (2019) and Pfaeffle et al. (2022)). Closer collaboration between landowners and practitioners implementing the work and academic institutions could increase the number of before-after study designs.

Calls for future research have been met with calls for standardized monitoring metrics (e.g., Rubin et al., 2017), which were also discussed in most practitioner interviews (Table 4). While a degree of flexibility in monitoring parameters and protocols is often required to address the goals of specific projects and stakeholders, we encourage practitioners to thoroughly assess their planned measurements to contextualize the success of LTPBR structure implementation. The need for both consistency and flexibility can be an opportunity for further collaboration between scientists, practitioners, and land managers to hone monitoring protocols. The range of monitoring metrics found by the meta-analysis of LTPBR literature (Table 1) could provide a guideline for future projects in order to remain consistent and comparable with past efforts.

Conclusion

PBR is increasingly being used across western North America due to its potential benefits for stream temperature, water and sediment storage, and vegetation across river corridors. Our review and meta-analysis of LTPBR projects showed that beaver dams, BDAs, and ORDs are generally (>80% of reported projects) storing water and sediment and increasing vegetation greenness and sometimes (<40% of reported projects) decreasing stream temperatures – all of which are commonly expected LTPBR outcomes – but that the magnitude of change depends on local mean annual precipitation, time since restoration, and structure type. Comparisons across LTPBR types allowed for a closer examination of how structures perform similarly (such as for increasing NDVI or changing stream temperature) and differently (such as for sediment and water storage). Cross-project comparisons provided insight into expected LTPBR outcomes both between sites of different character as well as at individual sites as regional climate warms.

Changing state laws have recognized the instream use of water for ecological restoration as a beneficial use of water rights, thus potentially increasing opportunities to use large-scale LTPBR to adapt river corridors to climate change. Restoration practitioners identified the need to collaborate with stakeholders and learn from consistent monitoring protocols to improve the use of LTPBR in the future. As the capacity and interest for stream restoration continues, instream LTPBR may be valuable for increasing resilience to climate change – particularly to rising stream temperatures and decreased streamflow – in fluvial ecosystems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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