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Sediment storage and shallow groundwater response to beaver dam analogues in the Colorado Front Range, USA

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Abstract

Enthusiasm for using beaver dam analogues (BDAs) to restore incised channels and riparian corridors has been increasing. BDAs are expected to create a similar channel response to natural beaver dams by causing channel bed aggradation and overbank flow, which subsequently raise water tables and support vegetation growth. However, lack of funding for monitoring projects post-restoration has limited research on whether BDAs actually cause expected channel change in the Front Range and elsewhere. Geomorphic and hydrologic response to BDAs was monitored in two watersheds 1 year post-restoration. BDAs were studied at Fish Creek, a steep mountainous catchment, and Campbell Creek, a lower gradient piedmont catchment from May to October 2018. At each restoration site, the upstream- and downstream-most BDAs were chosen for intensive study in comparison with unrestored reference reaches. Monitoring focused on quantifying sediment volumes in BDA ponds and recording changes to stream stage and riparian groundwater. Despite differences in physical basin characteristics, BDA pools at both sites stored similar volumes of sediment and stored more sediment than reference pools. Sediment storage is positively correlated to BDA height and pool surface area. However, BDAs did not have a significant influence on shallow groundwater. The lack of groundwater response proximal to BDAs could indicate that local watershed factors have a stronger influence on groundwater response than restoration design 1 year post-restoration. Systematic, long-term studies of channel and floodplain response to BDAs are needed to better understand how BDAs will influence geomorphology and hydrology.

KEYWORDS
beaver, beaver dam analogues, Front Range, pool sedimentation

1 | INTRODUCTION

Beaver dam analogues (BDAs) are increasingly used as low-tech, low-cost solutions to restoring degraded streams across the American West (Pilliod et al., 2017; Pollock, Lewallen, Woodruff, Jordan, & Castro, 2017). Widespread stream incision and degradation in the mountain West were recorded post-European settlement concurrent with beaver trapping and anthropogenic wood removal from streams (Naiman, Johnston, & Kelley, 1988; Polvi & Wohl, 2012). To restore streams once hosting North American beaver (*Castor canadensis*) across their historic range, BDAs are constructed to be permeable, instream structures made of wood, mud, and rock that are meant to mimic beaver dams and secondary effects associated with those dams (Pollock et al., 2017).

Beaver can significantly alter river corridors of low-gradient, low-discharge streams by dam building. River corridor here refers to the channel(s) and the adjacent floodplain, as well as the underlying hyporheic zone (Harvey & Gooseff, 2015). Beaver are ecosystem engineers and a keystone species, meaning they have a disproportionately large ecologic, geomorphic, and hydrologic effect on their environment compared with their abundance (Baker & Hill, 2003; Rosell, Bozser, & Parker, 2005). In low-order streams, beaver build channel-spanning dams that obstruct flow, cause backwater ponding, and decrease stream power and velocity (Naiman, Melillo, & Hobbie, 1986; Stout, Majerova, & Neilson, 2016). Decreased velocities allow for the aggradation of sediment and particulate organic matter behind dams, which raises the stream bed and reconnects incised channels with floodplains (Butler & Malanson, 1995; Pollock, Beechie, & Jordan, 2007). Channel-spanning dams also force a greater magnitude of overbank flow at a greater frequency and duration, causing stable, multithreaded channel networks to form (Polvi & Wohl, 2012; Westbrook, Cooper, & Baker, 2006). Increased overbank flooding from dams increases the lateral extent of groundwater recharge and hyporheic exchange, thus raising riparian water tables (Janzen & Westbrook, 2011; Westbrook et al., 2006). Increased lateral connectivity and decreased stream power create a positive feedback, allowing for a higher density of beaver dams within a reach until the river corridor reaches a dynamic, wet equilibrium known as a beaver meadow complex (Ives, 1942; Pollock et al., 2014; Polvi & Wohl, 2012; Ruedemann & Schoonmaker, 1938). Healthy beaver meadow complexes could have significant implications, including flood attenuation, carbon storage, denitrification, and mitigation of the effects of wildfire and drought on river corridors (Polvi & Wohl, 2012; Wegener, Covino, & Wohl, 2017; Wohl, 2013).

Beaver removal results in loss of ecosystem function and habitat. Valley bottoms can transform from wet, multichannel beaver meadows housing a diversity of plants and animals to a dry, single-threaded meandering channel after beaver loss (e.g., Green & Westbrook, 2009; Wolf, Cooper, & Hobbs, 2007). Abandonment and eventual failure of dams causes transport of trapped sediment and water downstream (Butler & Malanson, 2005), which causes ponds to drain, riparian water tables to decline, and streams to incise. Incision and lower water tables force geomorphic and ecologic systems into a drier stable state that is typically outside of the range of historical variability for valley bottoms with long histories of beaver habitation (Lewontin, 1969).

Beaver dam abandonment and subsequent valley bottom change were ubiquitous across the geographic range of North American beaver as populations dwindled from 60 to 400 million individuals prior to European settlement to an estimated 9 to 12 million beaver today (Jenkins & Busher, 1979; Naiman et al., 1988; Ringelman, 1991; Seton, 1929). In Colorado, widespread beaver trapping for fur between 1820 and 1840 led to a near extirpation of beaver by the late 19th century (Baker & Hill, 2003; Rutherford, 1964). State regulations enacted in the early 20th century protected beaver from being harvested except in instances where they threatened infrastructure, which caused beaver populations to rebound by the 1950s (Retzer, Swope, Remington, & Rutherford, 1956; Rutherford, 1964). Today, beaver populations are not officially monitored in Colorado, but beaver activity has been reported across the State. Still, loss of habitat and grazing competition by elk, moose, and cows has limited beaver reestablishment in some Colorado watersheds (Baker, Ducharme, Mitchell, Stanley, & Peinetti, 2005; Small, Frey, & Gard, 2016). Streams where vegetation loss, stream incision, or grazing conflicts limit the reintroduction of beaver could be prime for BDA restoration (Pollock et al., 2014).

BDAs can be installed in streams with limited current beaver habitat to accelerate stream recovery, reconnect streams with floodplains, and encourage beaver to build dams in the future (Pollock et al., 2012). BDAs are expected to cause the same complex channel response as natural beaver dams by storing sediment and causing overbank flooding upstream of the analogue (Pollock et al., 2012; Bouwes et al., 2016). Ideally, BDAs would be used to establish vegetation and habitat requirements to allow for the reintroduction of beaver as well as provide foundations for natural dams (Pollock et al., 2014).

The plethora of habitat, resource, and climate benefits associated with beaver dams explain enthusiasm for using BDAs as a restoration tool. However, lack of resources by watershed managers has limited systematic, scientific study of stream changes post-restoration, particularly studies quantifying channel change. Currently, channel response to BDAs can be estimated using empirical equations for natural beaver dams or from limited BDA studies. Studies from natural dams suggest that sedimentation might correlate to pool surface area and age, with larger and older BDA pools storing more sediment (Butler & Malanson, 1995; Naiman et al., 1986; Pollock, Heim, & Werner, 2003). Existing post-BDA restoration studies primarily focus on biological changes at large restoration projects (Pollock et al., 2012; Bouwes et al., 2016; Silverman et al., 2018). A study of steelhead response post-restoration reported significant aggradation and groundwater rise proximal to BDAs, but the study design included over 100 structures, which is not typical of most BDA projects (Bouwes et al., 2016).

Although restoration projects across the Colorado Front Range involve far fewer structures per stream reach, managers are interested in answering a similar question: Are BDAs in the Colorado Front Range effective at causing stream bed aggradation and raising water tables? BDAs in this region are typically installed to address incision and riparian vegetation concerns (Walsh Environmental, 2015; Wildland Restoration Volunteers, personal communication, May 2018). Understanding how physical basin characteristics such as slope, valley width, and channel morphology can be used to predict channel change post-restoration is important to guide expected outcomes and timelines for restoration projects. We quantified geomorphic and hydrologic response to BDA restoration projects in two watersheds in the Front Range.

2 | SITE DESCRIPTION

BDAs were monitored at Fish and Campbell Creeks in the Colorado Front Range (Figure 1). Fish Creek is a second-order stream underlain by Proterozoic Silver Plume Granite and Quaternary alluvium at the restoration site (Braddock & Cole, 1990). The creek heads at a lake within Rocky Mountain National Park and flows into a broad mountain valley before joining the Big Thompson River. Campbell Creek is a third-order stream underlain by early Triassic, late Permian Lykins Siltstone and Quaternary alluvium (Braddock, Wohlford, & Connor, 1988) that heads in the piedmont and joins the North Fork Poudre River. The two restoration sites were chosen because of landowner collaboration and diversity of physical basin characteristics (Table 1). By studying restoration in diverse watersheds, we can examine which geomorphic characteristics, if any, correlate with channel change post-restoration.

Incision is a driving factor influencing river corridor morphology on Fish and Campbell Creeks. In 2013, a 200-year recurrence interval flood on Fish Creek caused severe incision and channel migration (Yochum, Sholtes, Scott, & Bledsoe, 2017). Today, the active channel of Fish Creek is incised up to 3 m into the surrounding valley bottom, and beaver activity still exists on the original floodplain perched above the channel (Figure 1a). Campbell Creek has a much longer history of erosion and geomorphic change. In the early 1900s, water from the North Poudre Irrigation Canal was diverted through Campbell Valley, which significantly increased stream discharge and caused up to 12 m of erosion. Today, the active valley of perennial Campbell Creek is within a large, relatively stable arroyo incised into adjacent uplands (Figure 1b). In 2017, seven BDAs were installed along a 0.7 km reach of Campbell Creek and eight BDAs were installed along 0.3 km of Fish Creek to address ongoing incision concerns and to restore riparian habitat.

The scale and timing of BDA restoration are similar at Fish and Campbell Creeks, but BDA design differs between the two sites (Figure 2). BDAs in Fish Creek were constructed as traditional post and willow structures, with a few large (diameter > 10 cm) wood posts inserted in the stream bed and thinner branches woven between posts and stacked on the downstream end of the BDA. BDAs in Campbell Creek were constructed by partly burying large logs (diameter > 10 cm) in the banks and across the bed to create a wood jam perpendicular to flow similar to a wooden dam. Managers at both sites consider the structures of BDAs, which reflect the lack of a standard BDA design (Pollock et al., 2017).

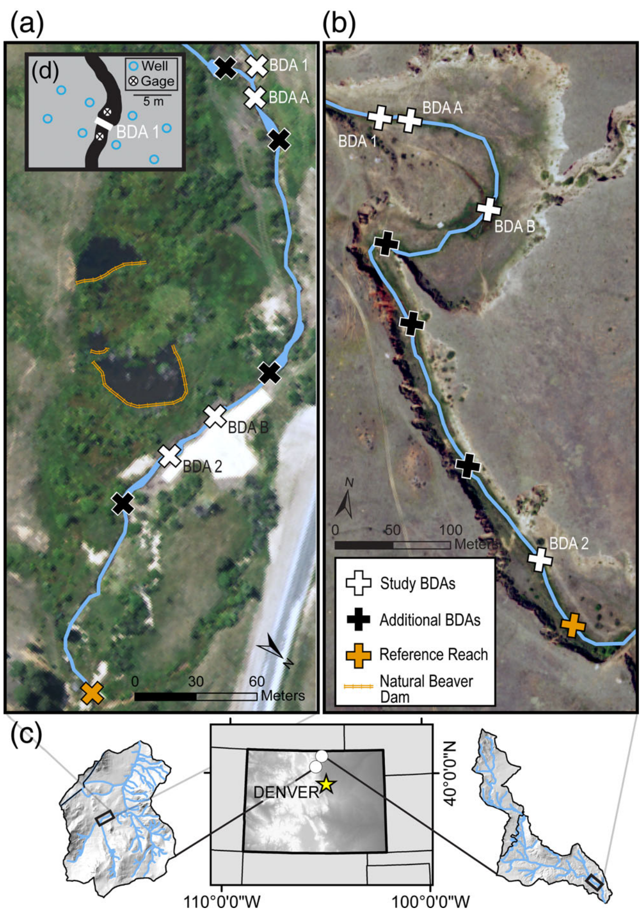

FIGURE 1 Map of restoration and experimental design. The location of all beaver dam analogues (BDAs) and natural beaver ponds at Fish Creek (a) and Campbell Creek (b) as well as the location of restoration sites within their respective watersheds in Colorado (c). Sediment surveys were conducted in pools upstream of the BDAs indicated by white symbols. Wells and stream gages were also installed upstream and downstream of BDAs 1 and 2 at both creeks for intensive hydrologic monitoring (d) [Color figure can be viewed at wileyonlinelibrary.com]

3 | METHODS

3.1 | Reach selection

In each watershed, two BDAs and a reference reach were monitored from May to September 2018, 1-year post-installation. The upstreammost and a downstream BDAs in sequence were monitored to capture potential variability in response as a result of position in the sequence. The upstream and downstream monitored BDAs are referred to as BDA 1 and BDA 2, respectively, at both Fish and Campbell Creeks (Figure 1).

Reference reaches were chosen to represent the channel pre-restoration as well as record any natural changes that occurred

TABLE 1 Physical basin and geomorphic characteristics of beaver dam analogue (BDA) restoration sites on Campbell Creek (Livermore, CO) and Fish Creek (Estes Park, CO)

Site name	Elevation[a] (m)	Restoration length[a] (km)	Number of BDAs	Mean valley slope	Upstream drainage area[b] (km^2)
Campbell Creek	5,555	0.68	7	0.008	8.1
Fish Creek	7,989	0.30	8	0.046	4.1

[a]Determined using Google Earth.
[b]Calculated using USGS Stream Stats.

(a)

(b)

FIGURE 2 An example of the buried log beaver dam analogue (BDA) design at Campbell Creek (a) and the traditional post-and-willow BDA design at Fish Creek (b). Differences in BDA construction at both sites allow for comparisons between designs [Color figure can be viewed at wileyonlinelibrary.com]

throughout the field season. At both sites, no proximal tributaries adequately represented the pre-restored main channel, and upstream reaches had significant geomorphic differences in valley bottom confinement. Therefore, reference reaches were chosen at least 10 bankfull widths downstream of restoration sites to decrease potential influences from the restoration itself.

3.2 | Surface hydrology

Stream stage was monitored through a series of stream gauges installed in May 2018 (Figure 1d). Five stream gauges were installed in each creek: two in the pools upstream of BDAs 1 and 2, two approximately one bankfull distance downstream of either BDA, and one at the reference reach. Gauges were built by housing a TruTrack WT-HR capacitance rod within a PVC casing attached to a metal fence post inserted into the stream bed. Stream stage was recorded every 15 min from late May to August.

3.3 | Shallow groundwater hydrology

To monitor groundwater dynamics, 20 shallow groundwater wells were installed across BDA 1, BDA 2, and the reference reach at each site in May 2018 using a grid design. Wells were installed to a depth of 1 m or shallower if the well reached a resisting layer. Wells were installed 1 and 5 m from bankfull on the left and right banks wherever an instream gauge was installed, for a total of eight wells at each BDA and four wells at each reference reach (Figure 1d). TruTrack WT-HR capacitance rods were installed in all 1-m distance wells to record water level at 15-min intervals from June to August. The depth of water in all wells across all sites was measured using a Solinst Water Level Meter (Model 102M) on approximately a weekly basis. These point measurements were the only data recorded at the 5-m wells, whereas point measurements were used to check continuously recorded water levels at the 1-m wells. Recorded water height was converted to groundwater table depth, which refers to the distance between the ground surface and the water table adjacent to the stream.

Groundwater time series were fit to a linear mixed model to determine whether a statistically significant difference existed between groundwater levels upstream and downstream of the BDAs. If BDA ponds increase groundwater recharge, a higher water table would be expected upstream. To reduce noise in the model, 15-min interval water table depth measurements were averaged by day at Fish Creek and by storm at Campbell Creek. Campbell Creek measurements were summarized by storm because wells were typically dry except following significant rainfall caused by summertime thunderstorms, whereas wells at Fish Creek had water all season long, allowing for averages to be calculated by day. Storms were chosen by hand with the help of rainfall data collected in Livermore, CO by CoCoRaHS (ID: CO-LR-250). Storms chosen for analysis were those with sufficient rainfall for at least five of the eight wells to respond at Campbell Creek. Wells were deemed "responding" if the water table rose above average within a 24-hr period post-rainfall, and then average depth to groundwater was calculated using measurements recorded within 24 hr of the start of well response. Mixed models were fit in R with the lme4, lmerTest, and emmeans packages using average groundwater table depth as the response at both sites (Bates, Maechler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2017; Lenth, 2019). Fixed effects included the position of the well (upstream or downstream of BDA), the time period (storm or day), plus position*period interactions. To account for the variability inherent to each BDA, stream bank, or individual well, these variables were included as random effects in the model.

3.4 | Channel surveys

Channel cross-sections and long profiles of the channel thalweg were surveyed at each creek in June and September 2018 using a TOPCON AT-B Series Auto Level and rod. Cross-sections were surveyed upstream and downstream of BDAs 1 and 2 and across the reference channel. Local channel slope and BDA height was extracted from long profiles, and width-to-depth ratio was extracted from channel cross-sections for further analysis in statistical regressions.

3.5 | Residual pool sediment surveys

Residual pool volume surveys were conducted in July and October 2018 in four BDA pools and a reference pool at each creek using an adapted V* method (Hilton & Lisle, 1993). Surveys were completed at Fish Creek on July 24, 2018 and October 12, 2018, and at Campbell Creek on July 23, 2018 and September 20, 2018.

The residual pool is the volume of water and fine-grained sediment that would remain in the pool if downstream flow was negligible, or essentially, the portion of a pool volume below the riffle crest forming the downstream lip of the pool. The residual pool was measured instead of the total pool in order to compare statistics across individual pools, surveys, and sites. When adapting the V* method to be used on BDA pools, we measured from the top of the analogue instead of the top of the riffle crest.

Residual pool surveys were conducted by systematically measuring water and fine-grained sediment depth at set intervals along channel cross-sections in the BDA or reference pool, with zero-area cross-sections assumed at either end of the pool (Hilton & Lisle, 1993). Residual pools beyond those instrumented at BDAs 1 and 2 were included in these surveys for additional statistical and explanatory power regarding reach-wide aggradation. To measure a pool, three to five evenly spaced cross-sections were selected perpendicular to flow along the length of the pool. Along each cross-section, water and sediment depth were systematically sampled at a consistent interval so that the widest cross-section of the pool would include at least five to seven point measurements. Water depth was measured using a rigid tape, whereas sediment depth was measured by pushing a piece of rebar into the fine bed sediment to the underlying coarse layer. This method was effective for quantifying fine-grained sedimentation because the pre-restoration bed material was significantly coarser than post-restoration aggraded material. Water and sediment depths were interpolated across entire ponds based on residual pool survey points.

Residual pool sediment volume was modelled from physical reach characteristics using a multiple linear regression (Ott & Longnecker, 2016). Independent (predictor) variables considered in the model were pool surface area, pool volume, channel slope, bed soil clay percentage, BDA height, upstream catchment area, and width-to-depth ratio. All independent variables except for catchment area were measured in the field. Channel slope, width-to-depth ratio, pool volume, and pool surface area were natural log transformed, and sediment volume was square root transformed in order to meet the model assumption of normality. Sediment surveys from Fish Creek and Campbell Creek were combined into the same multiple linear regression model for additional statistical power. A full multiple regression model was created for the response variable (sediment volume) that included all predictor variables using the *lm()* function in R. The significance of each predictor variable was tested at α = .05 to determine explanatory power of predictor variables. Akaike Information Criterion, corrected for small sample size (AICc) was used for selection of model variables: The model with the lowest AICc was chosen as the final model (Hurvich & Tsai, 1989). Model selection was performed using the *dredge()* function in the MuMIn R package (Barton, 2018).

4 | RESULTS

4.1 | Surface hydrology

Stage dynamics upstream and downstream of BDAs differs by site (Figure 3). BDAs increased upstream water surface area at both sites, creating a pond. The upstream ponds at Fish Creek were deeper than the creek immediately downstream of a BDA, whereas the ponds at Campbell Creek were shallower than the immediate downstream water stage. Shallow stage upstream of Campbell Creek BDAs contradicts the expected deep pools that would form as a result of

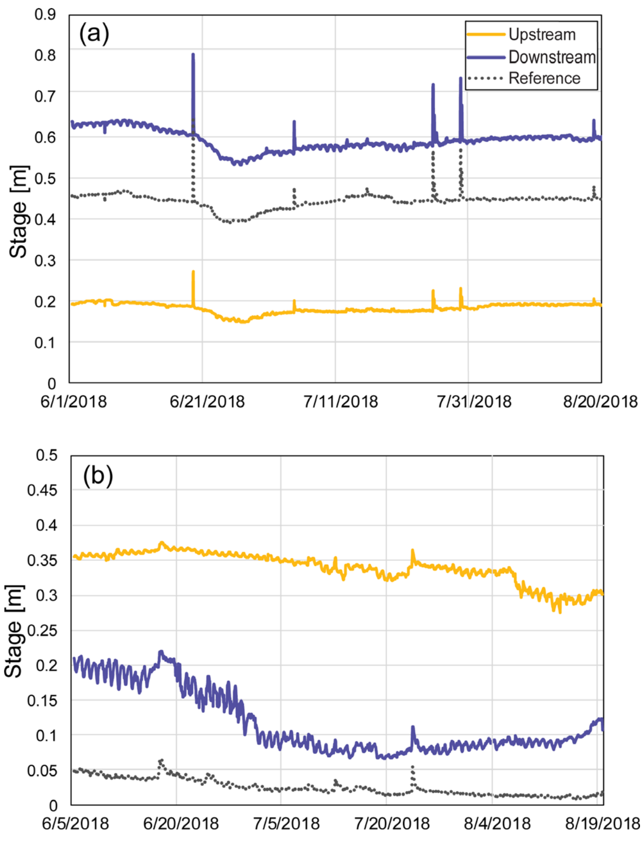

FIGURE 3 Stage upstream and downstream of beaver dam analogue (BDA) 2 at Campbell Creek (a) and Fish Creek (b). The black, dashed line represents the depth of water in a pool at the reference reach. By comparison, higher stage than the reference was recorded both upstream and downstream of the BDA at Fish Creek despite sediment aggradation (b). At Campbell Creek, sediment aggradation and downstream pool scour cause deeper water depths downstream of BDA 2 and very shallow pools to form upstream of the BDA (a) [Color figure can be viewed at wileyonlinelibrary.com]

backwater effects, which reflects proportionally higher sediment accumulation than expected within 1 year of installation.

4.2 | Shallow groundwater hydrology

Water table depth was averaged daily from June 5, 2018 to August 19, 2018, at Fish Creek as well as over seven storms between June 1, 2018 and August 21, 2018, at Campbell Creek (Figure 4). Storms large enough to be analysed occurred on June 19, July 5, 12, 15, 25, 29, and August 18, 2018, at Campbell Creek. Despite apparent differences in seasonal averages at Fish Creek, results from a linear mixed model comparing the difference in groundwater between well pairs for each day or storm at Fish and Campbell Creeks, respectively, found no significant difference in groundwater upstream of a BDA

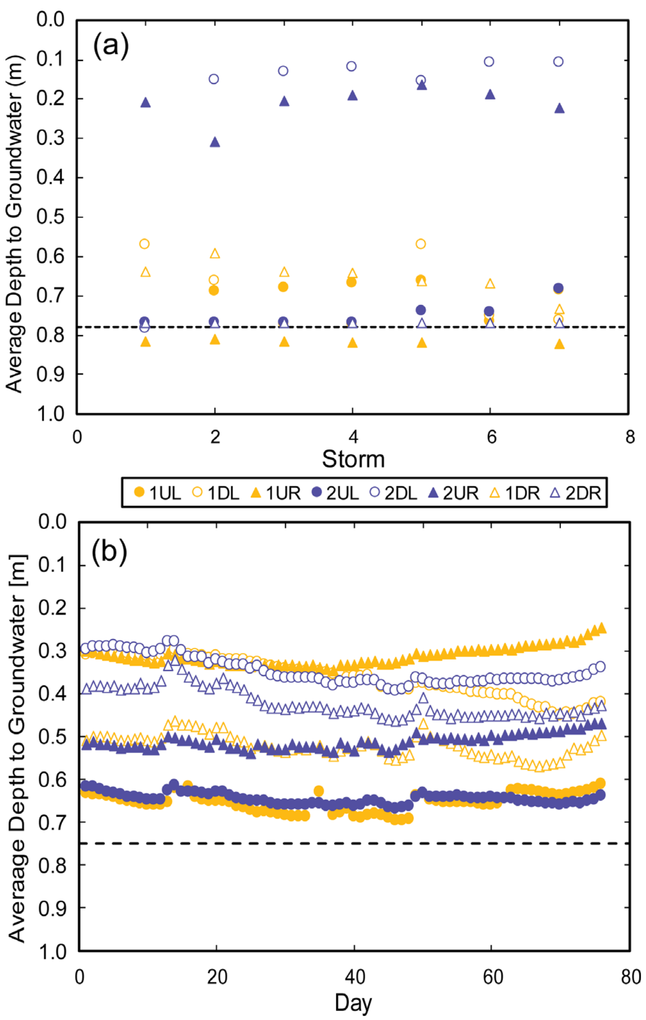

FIGURE 4 Average depth to groundwater by storm at Campbell Creek (a) and by day at Fish Creek (b). The dashed line represents the bottom of the well, below which the well was dry. Symbol colour, fill, and shape represent the beaver dam analogue (BDA), the location upstream or downstream, and the bank where the well was located. There is no clear groundwater pattern around BDAs at Campbell Creek (a). On average, the groundwater table was closer to the surface below BDAs than upstream of BDAs at Fish Creek (b) [Color figure can be viewed at wileyonlinelibrary.com]

compared with downstream ($p = .27$ and $p = .86$ for Fish and Campbell Creeks, respectively).

Though the studied BDAs did not statistically significantly raise upstream groundwater tables within the first year, comparing upstream and downstream water tables does not directly indicate whether a BDA is influencing groundwater recharge. Elevation of groundwater and stream stage proximal to BDA 1 at Campbell and Fish Creeks on July 19, 2018 and June 20, 2018, respectively, were plotted to further investigate recharge (Figure 5). Plotting water table elevation can reveal the water gradient and therefore the direction that water is moving. Fish Creek is a gaining stream downstream of BDA 1, meaning that water gradients suggest groundwater discharge into the creek (Figure 5). In contrast, Fish Creek is likely a losing stream upstream of BDA 1 because stage elevation is the same or slightly higher than surrounding groundwater. Therefore, BDA 1 at Fish Creek is causing groundwater recharge upstream of the structure compared with downstream or a non-restored reach. Campbell Creek was a losing stream both upstream and downstream of BDA 1, which suggests that the water table is consistently low enough that groundwater recharge would occur whether or not a BDA was installed. Because hyporheic exchange was not investigated at either site, comparisons between shallow groundwater tables and stream stage should only be viewed as a first-order approximation of groundwater movement. For example, clay soils at Campbell Creek could be limiting all interaction between the stream and groundwater, causing the creek to be perched above the water table with no interaction.

Most non-recording, 5-m distance wells were dry for a majority of the season at both sites and are therefore not discussed any further.

4.3 | Residual pool surveys

Residual pool and sediment volume were surveyed in four BDA pools and one reference pool per creek (10 pools total) from July to October 2018. Pools were surveyed twice to see if significant aggradation was occurring throughout the season 1-year post-BDA installation, with the exception of one pool at Fish Creek that was only surveyed once. However, residual pool and sediment volumes did not change significantly from one survey to the other ($p > .05$). The 19 individual surveys included BDAs beyond BDAs 1 and 2 at each site, and additional BDAs are named by their proximity to the instrumented BDAs. BDA A refers to the BDA directly downstream of BDA 1, and BDA B refers to the measured BDA directly upstream of BDA 2 for both sites (Figure 1). Reference refers to the reference pool at each site, which was a pool not created by a BDA.

Significant sediment aggradation occurred in pools created by BDAs compared with reference pools (Figure 6, $p = .0008$), which indicates that BDAs are significantly altering sediment storage on these creeks. BDAs at Campbell Creek store up to 3.2 m^3 of sediment, whereas BDAs at Fish Creek store up to 4.1 m^3 (Table 2). Despite substantially different basin characteristics (Table 1), BDAs at

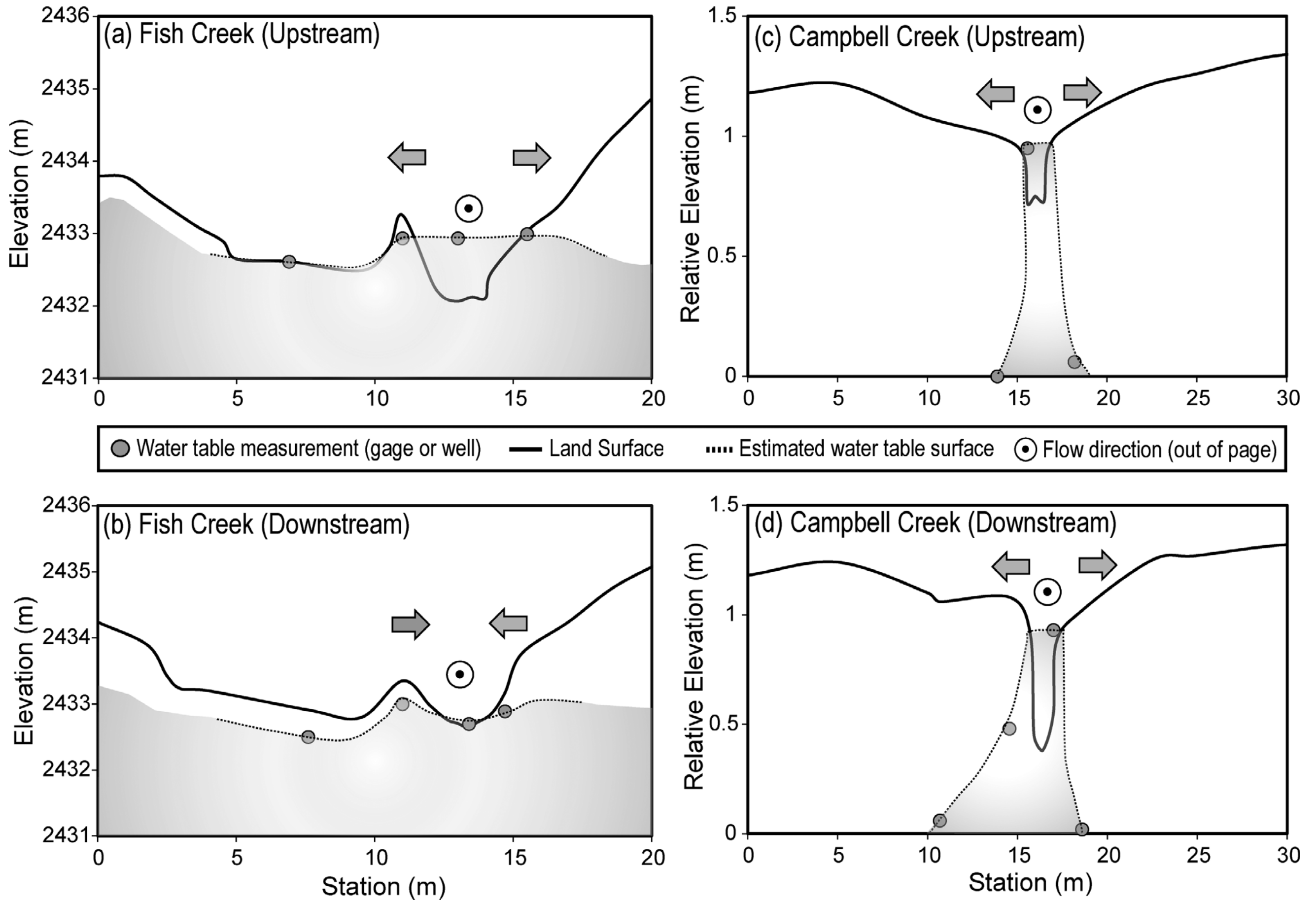

FIGURE 5 Absolute and relative elevation of surface and groundwater at upstream and downstream BDA 1 on Fish (a and b) and Campbell (c and d) Creeks. Where available, absolute elevation was used in lieu of relative elevation measured from channel cross-sections. Cross-sectional view of the water table is superimposed over surface topography. Groundwater table elevation is estimated from well and gauge points (grey circles). Arrows indicate the expected direction of exchange between the channel and shallow groundwater

Campbell Creek and Fish Creek stored statistically similar volumes of sediment (p = .946). However, when normalized by pool volume, Fish Creek stores a lower ratio of sediment than Campbell Creek (p = .001). Therefore, BDAs at Fish Creek are storing a similar magnitude of sediment in larger ponds compared with BDAs on Campbell Creek.

Pool volume, pool surface area, and BDA height had the strongest correlations to sediment volume (Table 3). A dredged multiple linear regression analysis revealed that a combination of BDA height and pool volume created a model with the lowest AICc (AICc = 3.4, adjusted R^2 = .86):

$$\sqrt{\mathit{Sediment\ Volume}} = 1.2 \cdot \mathit{BDA\ Height} + 0.17 \cdot \log(\mathit{Pool\ Volume}) + 0.68. \quad (1)$$

Predictor variables were transformed to satisfy model assumptions of normality, but do not have any physical basis in nature. Therefore, a second dredged linear regression model was created without transforming non-normal variables. Despite non-normal variables, the second model still met the assumption of residual homoscedasticity. By dredging the second model, sediment volume was revealed to be a function of BDA height and pool surface area (AICc = 35.9, adjusted R^2 = .83):

$$\mathit{Sediment\ Volume} = 3.3 \cdot \mathit{BDA\ Height} + 0.04 \cdot \mathit{Surface\ Area} - 0.1. \quad (2)$$

According to both multiple linear regressions, BDA height has the most explanatory power. BDA heights across the two restoration projects had a similar range, which explains why sediment volumes were not statistically different across watersheds (Table 2). Because the models were built with a small sample size (n = 19), the equations should not be used as a predictive model, but rather as a means of showing correlation.

5 | DISCUSSION

5.1 | Correlation between analogues and aggradation

Sedimentation models for BDAs can help managers understand which variables influence bed aggradation, which was a desired restoration

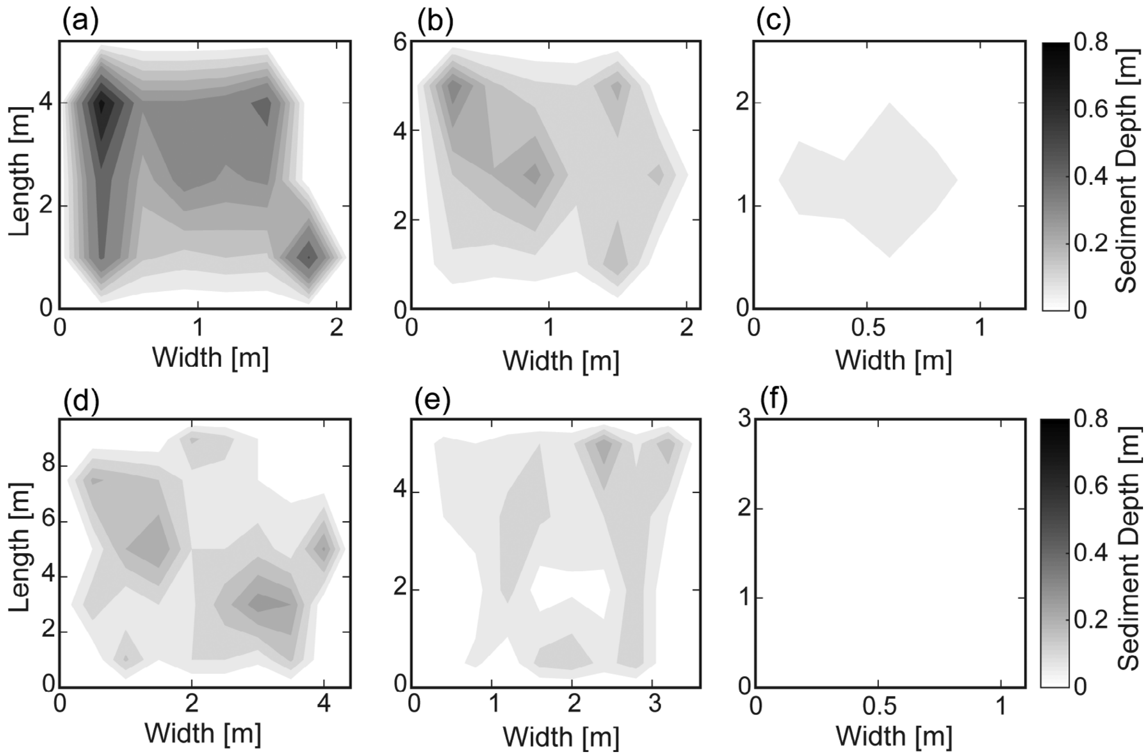

FIGURE 6 Examples of sediment depths measured in pools upstream of beaver dam analogues (BDAs) at Fish (a–c) and Campbell (d–f) Creeks during the second sediment survey. Sediment volume behind BDAs correlated strongly to BDA height. Therefore, the tallest BDA at both creeks (a and d) and the shortest BDA at both creeks (b and e) are juxtaposed to the reference pool (c and f). At both restoration sites, BDA 2 (a and d) were the tallest and BDA 1 (c and f) were the shortest built structures

TABLE 2 Upstream pool and stored sediment characteristics at four surveyed beaver dam analogues (BDAs) at Fish and Campbell Creeks in Colorado

	Fish Creek				Campbell Creek			
Variable	BDA 1	BDA A	BDA B	BDA 2	BDA 1	BDA A	BDA B	BDA 2
Height (m)	0.15	0.27	0.19	0.76	0.19	0.4	0.3	0.46
Pool volume (m^3)	2.5	4.2	5.9	17.9	0.6	2.5	1.3	1.7
Sediment volume (m^3)	1.2	1.2	1.9	4.1	1.1	3.2	2.2	2.1
Max water depth (m)	0.5	0.68	0.67	1.07	0.17	0.28	0.42	0.47
Max sediment depth (m)	0.24	0.34	0.34	0.33	0.34	0.5	0.76	0.74
Surface area (m^2)	10.9	30.1	8.3	11.2	12.0	23.2	27.3	41.9

outcome at both study sites. Because of small sample sizes, sediment models presented here should not be used predictively. Instead, variables included in the sediment equations represent general trends that could be useful for understanding future projects.

The three significant predictors of sediment volume—BDA height, pool volume, and pool surface area—all indicate that local geometry is influencing sedimentation more than watershed-scale characteristics. However, variables other than those included in the model could have an influence on sedimentation. For example, suspended sediment was not measured during monitoring, but likely influences how much sediment could accumulate behind dams. Campbell Creek should have a higher suspended sediment load based on lithology and climate. Measured variables nonetheless provide insight into the correlation between restoration design and outcomes.

BDA height is the only significant variable in both sedimentation models, which seems intuitively reasonable. If sedimentation behind a BDA is treated as a wedge forming approximately a triangular prism, the tallest part of the wedge would be buttressed against the BDA. Therefore, the maximum dimensions of the wedge would be controlled by the height of the BDA. Pollock et al. (2003) used physical dimensions of beaver ponds to estimate maximum sediment volume and included dam height as a significant predictor:

TABLE 3 List of predictor variables of sediment volume, including units, range, transformations used in the model, and *r* values

Predictor variable	Range	Transformation	*r* value[a]
Pool volume (m^3)	0.04–18.78	Natural log	0.809
BDA height (m)	0–0.76	None	0.808
Pool surface area (m^2)	2.7–45	Natural log	0.805
Catchment area (km^2)	3.85–8.13	None	–0.163
Channel slope	0.007–0.049	Natural log	–0.102
Width-to-depth ratio	2.5–19	Natural log	0.072
Clay (%)	21–25	None	0.038

Abbreviation: BDA, beaver dam analogue.
[a]Spearman *r* values between predictor variable and sediment volume calculated in R using *cor()* function.

$$V_m = \frac{0.5H^2W}{S}. \quad (3)$$

where H is dam height (in metres), W is dam width (in metres), and S is stream slope. Correlation between sediment and height, although intuitive, has not been recorded in previous field studies of beaver dam sedimentation. For example, Naiman et al. (1986) found no significant correlation between dam geometry and sedimentation in ponds in boreal forests of Canada.

The other two significant predictors—pool volume and pool surface area—are where the two sedimentation models diverge. Which model is better? Although both models explain sedimentation behind BDAs, correlation values suggest that Equation (1) is more suitable than Equation (2) (R^2 values of .86 and .83, respectively). However, pool volume is difficult to measure accurately in the field, and previous beaver dam sedimentation studies (e.g., Naiman et al., 1986) have not found pool volume to be a significant or simple predictor of sediment. Log transformation of the pool volume variable further decreases the usefulness of Equation (1), because a log transformation holds no physical meaning. Instead, a large change in pool volume would result in a small change in sediment volume. Conversely, surface area is easier to measure in the field or estimate from photographs and, because no transformation was necessary, the direct comparison makes more physical sense. Multiple studies have found pool surface area to be a significant predictor of sedimentation behind a beaver dam (Butler & Malanson, 1995; Naiman et al., 1986). Additionally, the differentiation between the two models is likely small, because pools with larger volumes are likely to also have larger surface areas.

The correlation between BDA sedimentation and pool surface area suggests that BDAs influence sediment similarly to natural beaver ponds. As a test, sediment volumes measured on Campbell and Fish Creeks were compared with maximum sediment volumes predicted by previously published beaver dam models (Figure 7). Measured sediment data were compared with the geometric relationship in Pollock et al. (2003) and the surface area-based equation from Naiman et al. (1986):

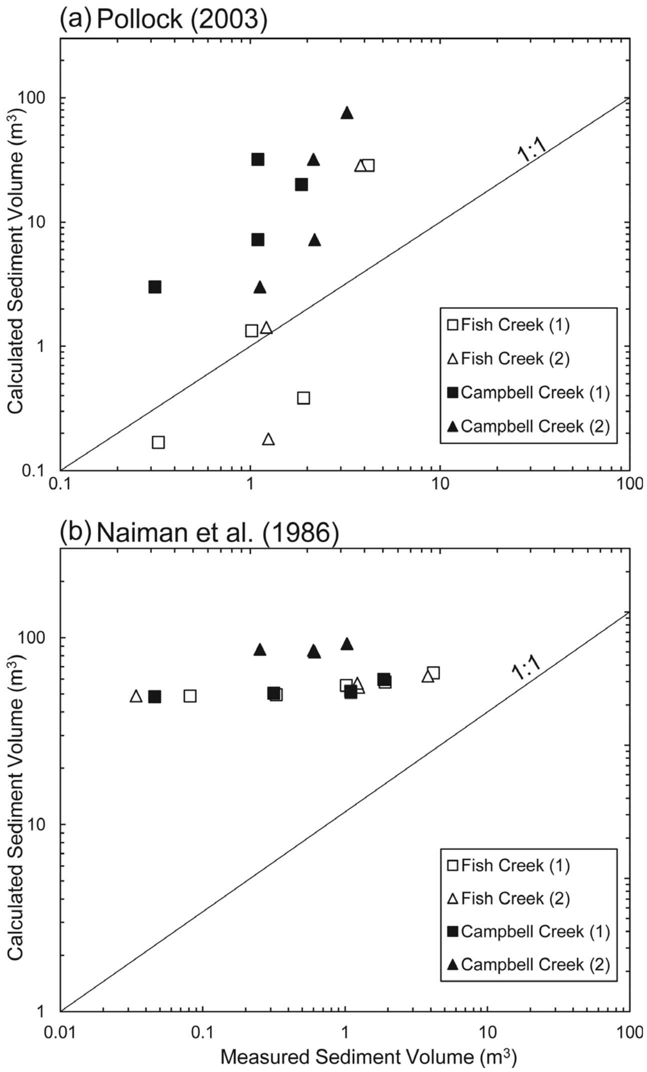

FIGURE 7 Measured sediment volumes compared to sediment volumes predicted by (A) $V_m = 0.5H^2W/S$ (Pollock et al., 2003) and (B) $S = 47.3 + 0.39 \cdot SA$ (Naiman et al.,1986). Shading and shape reflect the location and survey

$$S = 47.3 + 0.39 \cdot SA, \quad (4)$$

where S is sediment volume in cubic metres and SA is surface area in square metres.

Sediment volumes calculated using the Pollock and Naiman equations were much higher than sediment volumes measured behind BDAs in the field, except for a few pools at Fish Creek. Calculated sediment volumes should be higher than measured volumes. Pollock et al. (2003) estimates maximum sediment volume, which would likely not be reached within the first year after dam construction. Natural beaver dams and BDAs alike exhibit increasing sediment volumes with age (Butler & Malanson, 1995; Bouwes et al., 2016). Dams used to develop Equation (4) had a range of ages with many presumably over a year old, and all dams had higher surface areas (minimum surface area approximately 100 m^2) than measured BDA ponds; therefore, the current comparison extends below the reach of the original equation.

Differences between beaver dam sediment equations and measured BDA sediment could suggest that BDAs do not act like beaver dams. Most sediment volumes measured behind BDAs were lower than predicted values, which could imply that BDAs are less effective at trapping fine sediment than natural dams. Disparities between calculated and measured sediment volumes could also be because of age, extent, or permeability differences between the studied BDAs and modelled beaver dams. Natural beaver dams measured by Naiman et al. (1986) likely extended onto the floodplain and created pools reaching far beyond the channel banks, which is common for natural dams but not for the studied BDAs. Larger natural dams that extend onto the floodplain are less likely to pass suspended sediment than a BDA that could be overtopped or bypassed during high flow. Longer studies of BDA response could untangle whether discrepancies in sedimentation rates between beaver dams and the BDAs on Fish and Campbell Creeks are due to design, age, or some other factor.

5.2 | Groundwater response

The absence of a groundwater response was unexpected. Previous studies have monitored and described groundwater rise upstream of beaver dams in Colorado (Westbrook et al., 2006), and proximal to BDAs at a study on Bridge Creek, Oregon (Bouwes et al., 2016). However, groundwater on Fish and Campbell Creeks appears to be strongly controlled by multiple factors, including floodplain stratigraphy and the presence of natural dams.

Disparate groundwater response at wells surrounding the same BDA for the same rainfall event at Campbell Creek suggests that subsurface lenses of clay could be the dominant control or limitation to the water table. Higher water tables on the right banks of Fish Creek could be driven by a series of natural beaver dams higher on the floodplain past the right bank. Both site-specific explanations describe groundwater dynamics better than the presence of BDAs, which have no statistically significant influence on the water table.

BDA design relative to beaver dams might also explain groundwater response. Natural beaver dams near Fish Creek are much wider and pond more water than BDAs, which might be too small and/or permeable to cause significant groundwater rise at either creek. In August 2018, beavers adapted one BDA at Fish Creek, expanding the length of the dam and the size of the pond by approximately tenfold.

Lack of groundwater response could also be because of time since installation. Monitoring of BDAs occurred 1 year after restoration, and results may not be indicative of potential long-term groundwater response. Potentially, long-duration decline in riparian water tables following channel incision might take multiple years to reverse if water infiltrating into the bed and banks upstream from each BDA represents a small proportion of available riparian groundwater storage.

The indication that Fish Creek changes from a gaining to a losing stream around a BDA (Figure 5) could be evidence that larger groundwater changes will occur in future years after BDA restoration. Moreover, BDA 1 at Fish Creek proves that BDAs could change a gaining stream to a losing stream. However, if the stream is already losing, as at Campbell Creek, potential recharge from BDAs in the first year is still not enough to significantly raise the water table. Expectations for groundwater response following BDA installation should not be immediate, and further research is needed to understand the timeline of hydrologic response post-restoration.

5.3 | Design influences on BDA response

Construction differences between BDAs on Fish and Campbell Creeks beg the question of whether BDA design influences channel response. Differences in BDA construction between the creeks affected pool morphology post-restoration. Deeper pools persisted upstream of Fish Creek BDAs compared with downstream, whereas Campbell Creek BDAs elicited an opposite response. Differences in pool depth are likely a function of how much water overtopped BDAs on each creek throughout the snowmelt season. Campbell Creek BDAs were designed to allow overtopping during most of the season to avoid conflict with downstream water users. Constant overtopping created scour downstream of structures, which created deep pools and high stream stage immediately downstream of BDAs on Campbell Creek (Figure 3). Fish Creek BDAs were constructed to trap water and force ponding, which limited water downstream of the structure but increased water depths upstream. However, water surface area still increased upstream of BDAs at both sites, which means that ponds were created upstream of Campbell Creek BDAs despite the fact that BDAs did not increase stage upstream. Instead, upstream pools at Campbell Creek were shallow and filled with sediment. Assessing whether one design is better than the other depends on the intent of the restoration project.

Stopping incision and then promoting aggradation was cited as restoration goal for projects on Campbell and Fish Creeks. BDA designs at the two creeks both successfully trapped sediment and caused aggradation, and results suggest that BDA design has a significant effect on channel change post-restoration. As previously discussed, BDA height significantly correlates to and possibly influences sedimentation behind BDAs. Unlike pool morphology, sedimentation response was consistent across the two watersheds. The tallest BDAs stored the most sediment at both restoration sites, which means that the type of structure does not matter as much as the dimensions of the structure when addressing erosion concerns. Construction dominates over the watershed-scale variables examined in this analysis when explaining BDA-induced sedimentation.

6 | CONCLUSIONS

Enthusiasm for using BDAs as a restoration tool is increasing, but our results provide a cautionary note. Equating channel response to BDAs with channel response to natural dams is not always appropriate. Particularly, the efficacy of BDAs in raising water tables and promoting riparian vegetation is not demonstrated at the Colorado sites within the first year of installation. The data suggest that local factors such as soil grain size and regional water table gradients have a larger effect on groundwater than BDA presence. Systematic sampling across more watersheds and restoration sites could illuminate how local factors influence restoration outcome. Additionally, further studies where groundwater measurements can be made prior to restoration and over longer time periods would help elucidate how BDAs affect water tables in diverse settings.

BDAs can be used as an effective tool for causing aggradation and limiting incision. Similar to natural dams, sedimentation behind BDAs is correlated to surface area and BDA height, but maximum sedimentation is likely not reached within the first year of BDA installation. Future studies should quantify sedimentation in more ponds, across more restoration sites, for longer time periods. Future models of sedimentation should also investigate the influence of suspended sediment load on restoration outcomes. Long-term monitoring projects over years to decades will be needed to fully understand expected outcomes of BDA restoration projects.

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DATA AVAILABILITY STATEMENT

The data analyzed in this study are available from the corresponding author upon request.

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Note. Values for each variable are averaged across two residual pool sediment surveys completed in 2018, one year post BDA-restoration.

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