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RESEARCH ARTICLE

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Post-fire sediment attenuation in beaver ponds, Rocky Mountains, CO and WY, USA

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Abstract

We evaluated the post-fire sediment dynamics in beaver ponds to examine these ponds' contributions to sediment storage following disturbance. Beaver dams and beaver mimicry structures impound water and sediment, a function that is of growing interest in wildfire-prone landscapes. Wildfires typically lead to high sediment loading into rivers in the years following fire, constituting a disturbance to aquatic ecosystems and a challenge to water resource managers. Previous work establishes that beaver dams trap substantial volumes of sediment, but sedimentation appears spatially and temporally heterogeneous and it remains unclear the extent to which short-term pulses of sediment are attenuated by these structures. We examine the conditions under which beaver dams and beaver mimicry structures store post-fire sediment by quantifying the sediment volume of 40 ponds, about half of which were burned in large wildfires in the Colorado and Wyoming Rocky Mountains in 2020. The median relative volume of burned ponds is 85%, which is greater than the median for unburned ponds (58%), meaning that burned ponds store higher relative volumes of sediment when pond size is accounted for. Furthermore, sediment accumulated at a median rate of 3.0 cm/year over the entire history of the pond. Post-fire sedimentation rates, with a median of 20.4 cm/year, were an order of magnitude higher than pre-fire rates with a median of 1.8 cm/year. In addition, vegetation and geomorphic characteristics correlated with sediment storage in ponds. Sediment surveys confirmed that ponds with greater surface areas contain higher volumes of sediment. Additionally, older ponds and ponds abandoned by beavers stored higher volumes of sediment compared to recently constructed ponds, ponds actively maintained by beaver, and beaver mimicry structures. These findings demonstrate that beaver ponds and mimicry structures may function as sediment sinks capable of attenuating post-fire sediment. The biogeomorphic context, defined across multiple scales from the pond to the catchment, provides additional explanation for the wide range of sediment storage observed and remains an important consideration for beaver-based restoration, catchment sediment management, and resilience evaluation.

KEYWORDS
beaver, fluvial geomorphology, beaver mimicry, ponds, sediment, sedimentation, wildfire

1 | INTRODUCTION

Large-scale wildfires are becoming increasingly common and intense (Dennison et al., 2014). Wildfires increase the amount of sediment shed from hillslopes into fluvial systems (Kunze & Stednick, 2006) via reduced ground cover that alters hillslope roughness, evapotranspiration, and runoff generation (Blount et al., 2020). Intense heat also decreases infiltration rates by altering soil properties (DeBano, 2000; Ebel & Moody, 2017). High-severity fires combust vegetation more completely, which decreases canopy interception of precipitation (Stoof et al., 2012). Exposed sediment paired with increased infiltration excess overland flow contributes to greater hillslope erosion rates after fire (Moody & Martin, 2001). The highest rates of sediment loading occur immediately following fire, declining rapidly in subsequent years as soil recovers and vegetation regrows (de Dios Benavides-Solorio & MacDonald, 2005; Ebel, 2020; Rathburn, Shahverdian, & Ryan, 2018).

Influxes of sediment to rivers impact drinking water quantity and quality, water supply infrastructure, and aquatic habitat (Rust et al., 2018). The period after fire constitutes a "window of disturbance" when sediment flux is highest (Figure 1), and water supply is most vulnerable (Sass et al., 2012). Structures that capture in-channel sediment may temporarily reduce loads during this critical post-fire period (Robichaud, Beyers, & Neary, 2000). River corridors modulate sediment movement and contribute to catchment resilience to disturbance, especially where there is a high degree of physical complexity such as multithread channels or logjams (Rathburn, Shahverdian, & Ryan, 2018; Wohl et al., 2022). Resilience in ecological systems consists of both resistance to and recovery from disturbances such as wildfire (Yi & Jackson, 2021).

Beavers (Castor spp.) are geomorphic agents and ecosystem engineers whose activities alter landscape processes (Brazier et al., 2021; Larsen, Larsen, & Lane, 2021). Beaver dams increase river corridor spatial heterogeneity and contribute to feedback loops that increase sediment attenuation (Polvi & Wohl, 2012, 2013; Wohl et al., 2022). Beaver ponds actively store sediment across a range of landscapes (Butler & Malanson, 1995; Puttock et al., 2018). Beavers produce high water tables and large areas of surface water which enhance landscape resistance to burning while also facilitating vegetation regrowth after fire (Fairfax & Whittle, 2020). Beaver mimicry structures such as beaver dam analogues (BDA) entice beavers to streams and promote aggradation (Pollock, Beechie, & Jordan, 2007). Given the growing popularity of beaver-based restoration and mitigation approaches, there is a need to quantify the effectiveness of beaver ponds and mimicry structures at capturing post-fire sediment (Jordan & Fairfax, 2022). Sediment attenuation in ponds could temporarily decrease sediment transport downstream, serving as a buffer and increasing the resilience of receiving waters to wildfire disturbance.

Previous research has demonstrated that sedimentation rates in beaver ponds are higher than in surrounding channels and other wetland types, but rates may vary greatly between ponds and through time (John & Klein, 2004). A positive relationship between beaver pond surface area and sediment storage is well-established (Butler & Malanson, 1995; Naiman, Melillo, & Hobbie, 1986; Puttock et al., 2018). Additionally, pond age logarithmically relates to sediment volume (Bigler, Butler, & Dixon, 2001; Butler & Malanson, 1995; Meentemeyer & Butler, 1999). Beavers frequently build ponds in sequences along a channel, and the location of a pond in a sequence may correlate with the volume of sediment stored (Butler & Malanson, 1995; Puttock et al., 2018). However, the thickness of pond sediments is highly heterogeneous both within a pond and between ponds along stream reaches (Bigler, Butler, & Dixon, 2001; Butler & Malanson, 1995; John & Klein, 2004; Meentemeyer & Butler, 1999). Little research exists on beaver pond retention of excess sediment after disturbances such as wildfire.

Our objective is to evaluate the conditions under which beaver ponds and BDAs attenuate post-fire sediments. We hypothesize that (i) burned ponds will contain greater sediment volumes compared to unburned ponds, (ii) post-fire sedimentation rates will exceed pre-fire rates, and (iii) sediment volumes will correlate with potential explanatory variables, including the burn severity and vegetation cover within the contributing catchment, catchment drainage area, pond position

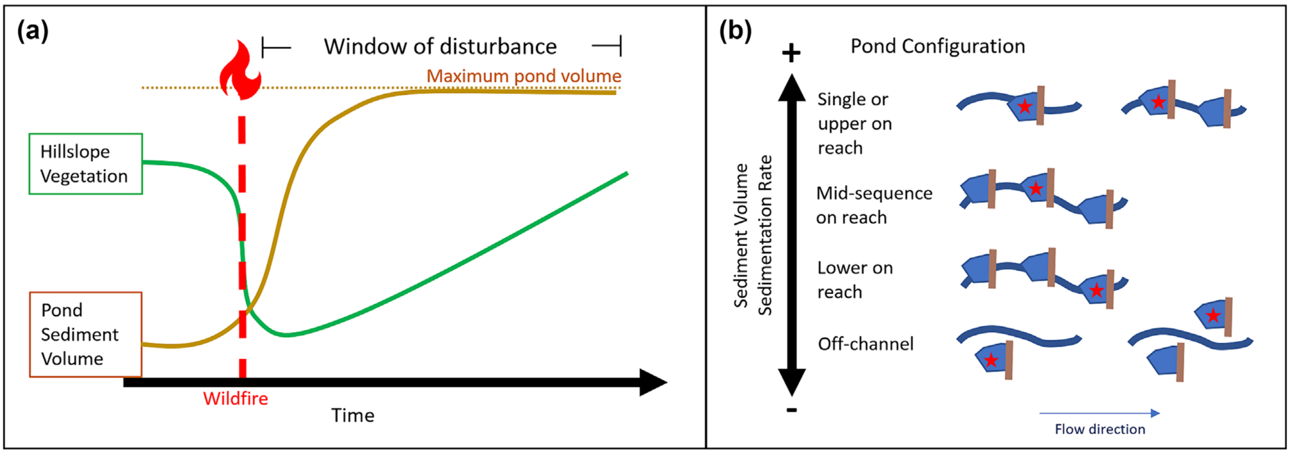

FIGURE 1 (a) Conceptual diagram illustrating inferred beaver pond sediment volume in relation to hillslope vegetation as a function of time since wildfire. Volumes and rates of sedimentation are expected to increase after fire. Ponds may fill to a maximum sediment volume governed by pond geometry. Dams may breach and lose sediment or vegetation regrowth may stabilize ponded sediment. (b) Sedimentation is also expected to vary as a function of pond position in relation to other ponds on the reach and to the stream channel. Red stars indicate the pond under consideration with the expected relative sediment storage along the y-axis. [Color figure can be viewed at wileyonlinelibrary.com] in relation to the channel (on or off channel) and to other ponds, pond age, and beaver activity. We examined pre- and post-fire sediment conditions with a survey of ponds in the Rocky Mountains.

2 | METHODOLOGY AND METHODS

We pursued two lines of evidence to evaluate sediment dynamics in natural beaver ponds and ponds impounded by beaver mimicry structures, henceforth collectively referred to as ponds. We quantified the current and remaining sediment storage capacities within ponds with sediment depth surveys, and we calculated sedimentation rates by analyzing stratigraphy within sediment cores. Burned and unburned ponds comprised our study sites. Aerial imagery analyses provided additional information about pond histories, and geospatial datasets informed catchment characteristics.

2.1 | Study area

Several large wildfires burned in Colorado in 2020, providing an opportunity to study post-fire sediment dynamics in ponds. The study area encompasses areas burned in the Cameron Peak (845 km^2), East Troublesome (784 km^2), and Mullen (716 km^2) Fires (Figure 2). Fires of varying severity have burned in the Rocky Mountain region for millennia, forming part of the disturbance regime that shapes ecology and biogeochemical cycles (Dunnette et al., 2014), but modern fires differ from the historical record in their size, intensity, frequency, and the elevations at which they burn (Higuera, Shuman, & Wolf, 2021).

The study area is predominantly underlain by crystalline rocks, with thin, coarse, and permeable soils on hillslopes. Valleys contain Quaternary deposits of glacial drift, colluvium, and alluvium. During the Pleistocene, glaciers deposited till comprised of poorly sorted crystalline clasts as well as moderately sorted glaciofluvial sediments (Madole et al., 1998). Glacial deposits form thick sediment packages in high alpine valleys, typically with weakly developed soils (Kramer, 2011; Madole et al., 1998). Glacial landforms including moraines, outwash terraces, and overfit valleys form the physical template for beaver occupation.

Ponds in the study area range in elevation from 2366 to 2734 m (7762–8969 ft). Persistent wintertime snow accumulation may occur at these elevations (Harrison et al., 2021). Winter snowmelt and summer thunderstorms are the dominant sources of stream runoff. Convective summer thunderstorms locally generate high-intensity, short-duration rainfall (Doesken et al., 2003). These storms can produce flooding, initiate mass movements, and transport large volumes of sediment (Anderson, Anderson, & Anderson, 2015; Rathburn, Shahverdian, & Ryan, 2018). Headwater regions contribute the majority of drinking water to major population centres: the Cache la Poudre River catchment, much of which burned in the Cameron Peak Fire, provides drinking water to more than 350, 000 people (Smith et al., 2011).

2.2 | Field and sediment surveys

We completed field and sediment surveys and collected sediment cores from ponds between June and August 2022. We visited a nearly equal number of ponds in burned and unburned areas. In the field, we classified ponds' burn status, beaver activity, and position in relation to the channel and other ponds. We looked for evidence of burning directly around the pond including charred vegetation and fire-altered soils. Fresh beaver chew, green vegetation in the dam structure, and local knowledge evidenced actively occupied beaver ponds. In contrast, abandoned ponds had deteriorated dams with extensive vegetation growth on the dam structure. Ponds impounded by beaver mimicry structures varied in construction method but were uniformly classified as BDAs. These structures were entirely human constructed, with no evidence of beaver contributions to the dam structure. We further classified ponds as on- or off-channel during low-flow conditions at the time of the field survey. This classification described the likelihood of sediment delivery from the channel to the pond. Additionally, we noted each pond's position in relation to other ponds along a reach. Reaches were defined as distinct lengths of river

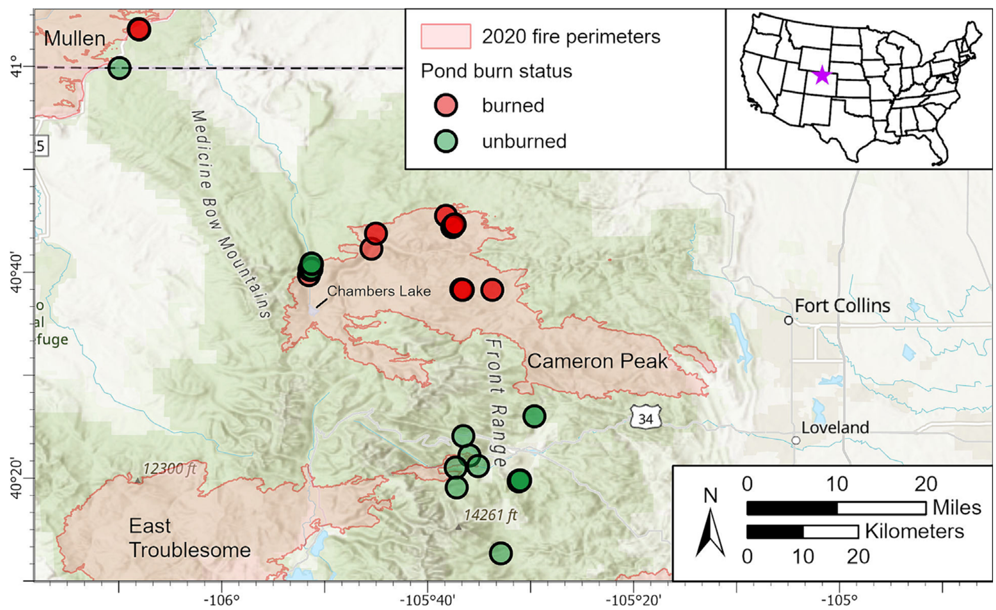

FIGURE 2 Locations of ponds included in this study, categorized by their burn status. Red outlines indicate the perimeter of the large wildfires that burned in 2020. [Color figure can be viewed at wileyonlinelibrary.com]

corridor separated by tributary input. Ponds were classified by whether they were the only pond on a reach, "single"; if they were the upstream-most pond along the reach, "upstream"; or if they were downstream of other ponds on the reach, "downstream." We did not include breached dams with no ponded water. Dense vegetation made it difficult to detect all ponds from the ground, so we used recent satellite imagery to verify field observations of pond sequencing. The sequencing order counted all ponds on a reach including ponds that were not field surveyed.

We surveyed the perimeter of ponds with a Topcon GR-5 RTK-GPS with 0.01 m horizontal accuracy. Alternate GPS devices were used to measure some ponds due to equipment issues, fully described in Dunn & Stich (2024). The perimeter was defined by the presence of open standing water or standing water among wetland vegetation that appeared inundated for much of the year. Equally spaced transects were established perpendicular to each pond's longest axis, with a target of five transects per pond, ranging from three to eight depending on the pond size. We surveyed sediment thickness at field-scaled intervals ranging from 0.1 to 3 m along each transect line (Dunn & Stich, 2024). We measured the water depth with a tape measure and the depth to the sediment base with a 2.4-m (8-ft) length, 8-mm (5/16-in) diameter tile probe marked with 5-cm intervals. The tile probe was pushed through the unconsolidated pond sediments until refusal indicated a compacted layer.

Pond perimeters and transect data were used to calculate sediment and water volumes. The ArcGIS Pro Spline with Barriers tool interpolated water depth, sediment base depth, and sediment thickness between transect survey points, bounded by the pond perimeter using a 0.5-m grid cell size. The sum of sediment thicknesses multiplied by pond area gave the pond sediment volume. The relative sediment volume (V^*) was calculated as the proportion of the total pool volume that contained sediment (Lisle & Hilton, 1992). V^* is independent of discharge and pond size, allowing for comparison between ponds. Notably, total sediment volume differs from relative volume in that sediment volume is an absolute measured amount rather than a percentage. Sediment volumes from individual ponds were summed to calculate reach sediment storage for 17 unique reaches.

We assumed that the water level at the time of survey represented the maximum depth of the pond which was supported by our observations of vegetation types around the pond perimeter. Many abandoned dams were partially breached, such that pond water levels were controlled by the breach as well as inflows. In actively maintained ponds, beavers may increase the dam height, resulting in pond enlargement and increased storage. Thus, the reported relative volumes should be taken as minimum values.

2.3 | Sedimentation rates

We selected two locations within each pond to collect sediment cores, although in exceptionally small or large ponds the number varied from one to four cores. We targeted locations with the thickest sediments to obtain the longest record of sedimentation. Furthermore, we attempted to core different parts of the pond to capture the spatial variability in sediment deposition. Cores were collected by pounding a 1.8-m (6 ft) long, 1.9-cm (1.75 in) inner diameter polycarbonate tube into pond sediments until refusal.

We analyzed changes in charcoal concentration with depth (Dunn & Stich, 2024). We conservatively interpreted the uppermost increase in charcoal concentration as indicating the most recent wildfire. Sediments below the increase in charcoal were classified as pre-fire and sediments above were classified as post-fire. Cores from ponds located in unburned catchments were uniformly classified as unburned, even when low levels of charcoal were detected.

The age of beaver ponds was estimated from Google Earth imagery (Dunn & Stich, 2024). Images were available at most sites from the years 1985, 1999, 2005, 2011, 2013, 2016, and 2019. For ponds visible in the oldest available image, the age of that image was used as a minimum pond age. Otherwise, the pond age was estimated from the midpoint between the year a pond first appeared in imagery and the year of the preceding image. The oldest period of pond occupation was used for sites with multiple periods of beaver activity. The year of BDA construction was known and thus not estimated from imagery. Pond ages were summarized into three age classes because of the inconsistent availability of imagery. In this classification, ponds established before 2000 CE were considered old, those dating between 2000 and 2015 were moderate, and those established after 2015 were recent.

We calculated three types of sedimentation rates from each sediment core (Dunn & Stich, 2024). The first, total sedimentation, described the average rate of sediment accumulation at the core location since pond construction. It was calculated for each sediment core by dividing the total core thickness by the age of the pond, and the mean rate was used in analysis for ponds with more than one core. The second, post-fire sedimentation rate, described the rate of sediment accumulation in the two years after wildfire. The rate was calculated by dividing the thickness of post-fire sediments by the number of years elapsed since the 2020 fires. Finally, pre-fire sedimentation rates were calculated by dividing the pre-fire sediment thickness by the pond age at the time of the fire.

2.4 | Catchment and valley characteristics

Catchments were delineated with the ArcGIS Pro version 3.0.2 Watershed (Ready To Use) tool (Dunn & Stich, 2024). The tool used the ponds' field surveyed locations to delineate catchments from a cloud-hosted, pre-processed version of the 30-m resolution National Elevation Dataset (NED). The pond locations were manually adjusted where necessary to reflect the field condition of whether the pond was connected to the channel. These catchments were considered representative of the current drainage area and were used to calculate burn, vegetation, and geomorphic characteristics. Historical imagery and field characteristics suggested that many ponds that are currently disconnected from the channel were originally connected. Accordingly, we ran a second catchment delineation with a 250-m pour point snap tolerance to reflect historically connected pond conditions. Both the current drainage area and historical drainage areas were used as explanatory variables in regression analysis.

We used the current drainage area to examine potential catchment scaling impacts on sediment volume. We divided the total pond sediment volume by the current drainage area to generate a normalized sediment volume which was analyzed as a response variable.

Catchment-scale burn characteristics were calculated from published spatial datasets. We checked the recent history of fire occurrence by intersecting the catchment layer with the WFIGS — Wildland Fire Perimeters Full History dataset (WFIGS Wildland Fire Perimeters Full History, n.d.). The burn severity within each catchment was summarized from the Soil Burn Severity dataset for each major fire (USDA Forest Service, Geospatial Technology and Applications Center, BAER Imagery Support Program, 2021, 2020a, 2020b). Burn severity was incorporated into two metrics: the total percent of each catchment area burned at any severity, and the percent burned at moderate and high severities.

The normalized difference vegetation index (NDVI) is a measure of greenness and an indicator of vegetation cover. We compiled Landsat 8 satellite images (30 m resolution) from July through September for the years 2019, 2021, and 2022 with a Google Earth Engine script. The script applied a cloud mask filter and formed composite rasters with the median NDVI for each summer. We then computed summary spatial statistics in ArcGIS Pro. We used the median 2019 NDVI values to represent the pre-fire condition and 2022 NDVI values for the post-fire condition. Additionally, the magnitude of post-fire vegetation recovery was measured as the difference in median NDVI values between 2021 and 2022. The three vegetation metrics were analyzed at two scales: catchment and local. The local zone for analysis consisted of a 200-m buffer around the beaver pond perimeters.

Geomorphic characteristics were calculated from 10 m digital elevation models (DEMs) and included relief ratio, mean catchment slope, valley gradient, and valley width (USGS, 2023a; USGS, 2023b; USGS, 2023c). Slopes, calculated as the percent rise with the ArcGIS Pro Slope tool, were averaged for each catchment. Valleys were visually identified using both the DEM shaded relief and vegetation changes in satellite imagery. We calculated valley gradient by digitizing 100 m horizontal lines along the valley axis from each pond, and then computing the difference in elevation at the start and end points. The valley width was calculated by digitizing a line perpendicular to the valley axis at each pond location. In incised reaches, we measured the width of the historical floodplain.

2.5 | Volumetric sediment accumulation rates

The average volume of sediment accumulated per year in ponds was computed as well. The volume of sediment stored in the pond, measured by probing, was divided by the age of the pond. We also computed estimates of catchment sediment export based on published background exhumation rates. Foster et al. (2015) found a mean exhumation rate of 3.1 cm/k.y. within their study area in the Colorado Rocky Mountains. We converted this value to an annual rate and multiplied by each pond's catchment area to give the volumetric rate in cubic meters per year. We divided the volumetric sediment accumulation rates by catchment export rates to estimate the proportion of the long-term catchment sediment flux captured by ponds.

2.6 | Statistical analyses

Statistical analyses were conducted using the R 4.2.2 software and the following packages: tidyverse, rstatix, broom, and betareg (Cribari-Neto & Zeileis, 2010; Kassambara, 2022; Lenth, 2023; R Core Team, 2022; Wickham et al., 2019). Explanatory variables included burn, vegetation, geomorphic, and pond characteristics (Tables 1, 2, and 3). Response variables included both pond and reach sediment volumes, sediment volumes normalized by drainage area, and the relative sediment volume of each pond. Linear regression models were used to evaluate the strength and significance of pairwise relationships between each continuous explanatory variable and the sediment volume and normalized sediment volume. Both response variables were right-skewed, so a cube root transformation was applied to sediment volume and a log-10 transformation to normalized sediment volume to meet the assumption of normality, evaluated with the Shapiro–Wilk test. The R^2 value indicated the goodness of fit, and residuals were visually examined to evaluate model assumptions. Beta regression was used to model the distribution and response of the relative volume to all continuous explanatory variables, as a normally distributed proportion (Ferrari & Cribari-Neto, 2004; Kieschnick & McCullough, 2003). The pseudo R^2 was used to evaluate the goodness of fit of the beta regression models.

Non-parametric tests were used to evaluate the significance of differences within categorical explanatory variables. The Kruskal–Wallis rank sum test was used for categories consisting of two groups, and Dunn's test was used for categories with three groups (Dunn, 1961; Kruskal & Wallis, 1952). Additionally, the total sedimentation rate of point locations within ponds was described, and pre- and post-fire sedimentation rates were compared for a subset of ponds with available data using the paired samples Wilcoxon signed rank test (Wilcoxon, 1945). All computed p-values were evaluated for significance using a threshold of $\alpha = 0.05$.

3 | RESULTS

Our field surveys included a total of 48 ponds but we excluded three ponds from our analysis that did not meet our fire occurrence or pond definition criteria (Dunn & Stich, 2024). We did not conduct sediment surveys or collect cores at five of the ponds visited, so these were also excluded from the analysis, leaving a total of 40 ponds. Tables 1, 2, and 3 summarize explanatory and response variables across the remaining 40 sites.

The ponds varied in size with surface areas ranging from 16 to 6361 m^2, and a median of 640 m^2. The size of the catchments varied greatly. Under current conditions, the catchments ranged in size from 0.0045 to 103 km^2 with a median of 3.4 km^2. In contrast, the minimum historical catchment area was 1.6 km^2 and the median area was 16 km^2. Pond catchments were moderately steep with a median slope of 28% and median relief ratio of 0.16. Around ponds, the median valley width was 117 m, and the median valley gradient was 2.0%. The areas immediately surrounding ponds had greater vegetation cover than catchments as a whole, both before and after fire. In 2019, the local vegetation cover median was 0.25 compared to 0.20 for catchments; in 2022, the local vegetation cover median was 0.22 compared to 0.16 for catchments. Median vegetation cover lessened after the fire, at both the local and catchment scale. Vegetation cover slightly increased between the 2 years following fire at the catchment scale with a median recovery of 0.0078; however, it decreased locally with a median of -0.0071.

TABLE 1 Summary of continuous burn, pond, and sediment characteristics by pond category. The median, standard deviation, minimum, and maximum values for continuous variables are listed for each categorical group, and summarized for all ponds and all reaches.

Category		Burn								Pond				Sediment											
Variable		Percent catchment burned				Percent catchment burned at moderate and high severity				Pond surface area, m^2				Sediment volume, m^3				Sediment volume normalized by catchment area, m^3/km^2				Percent relative volume			
Group	*n*	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max
Burned	21	48	43	0	100	14	28	0	68	631	1349	66	6361	563	1083	23	4888	164	11,786	1	53,638	85	15	43	100
Unburned	19	0	29	0	88	0	13	0	54	737	1413	16	5661	361	928	4	3665	45	18,837	<1	56,546	58	12	30	74
On-channel	25	37	43	0	100	10	25	0	68	315	1624	16	6361	241	1211	4	4888	41	10,855	<1	53,638	64	21	30	100
Off-channel	15	0	39	0	100	0.0	22	0	66	926	761	332	3099	763	540	361	2,353	796	20,145	88	56,546	72	15	54	100
Single	6	17	42	0	88	6.5	27	0	57	977	2117	16	5661	343	1389	6	3665	8	23,079	<1	56,546	57	13	39	74
Upstream	8	9.1	50	0	100	5.0	30	0	68	480	1159	54	3099	504	873	8	2353	162	14,248	1	40,850	80	20	44	100
Downstream	26	30	41	0	100	8.8	22	0	68	633	1218	32	6361	491	1001	4	4888	324	15,061	<1	53,638	70	19	30	100
Active	6	6.9	35	0	88	4.3	21	0	54	747	2871	215	6361	306	2132	131	4888	25	751	4	1890	53	12	39	74
Inactive	28	48	43	0	100	12	26	0	68	763	752	66	3099	628	612	23	2353	406	18,187	1	56,546	77	15	43	100
BDA	6	0	7.8	0	19	0	1.8	0	4.4	58	34	16	114	12	9	4	27	1	1	<1	3	47	13	30	64
Recent	14	6.9	39	0	100	2.2	26	0	68	127	1477	16	5661	79	958	4	3665	3	26	<1	89	55	22	30	96
Moderate	9	48	47	0	100	8.7	18	0	57	790	956	322	3099	416	748	194	2353	1890	20,228	11	53,638	72	12	43	81
Old	17	39	41	0	100	13	26	0	66	863	1436	216	6361	756	1095	226	4888	462	18,293	48	56,546	82	17	54	100
All ponds	40	19	42	0	100	8.7	24	0	68	640	1363	16	6361	465	1014	4	4888	150	15,853	<1	56,546	70	19	30	100
All reaches	17	18	38	0	100	8.6	25	0	68	--	--	--	--	913	2010	6	5434	173	13,707	<1	56,546	--	--	--	--

TABLE 2 Summary of continuous vegetation characteristics by pond category. The median, standard deviation, minimum, and maximum values for continuous variables are listed for each categorical group, and summarized for all ponds and all reaches.

Category	Vegetation																							
Variable	Pre-fire catchment vegetation cover (median NDVI 2019)				Pre-fire local vegetation cover (median NDVI 2019)				Post-fire catchment vegetation cover (median NDVI 2022)				Post-fire local vegetation cover (median NDVI 2022)				Post-fire catchment vegetation recovery (median ∆NDVI 2021–2022)				Post-fire local vegetation recovery (median ∆NDVI 2021–2022)			
Group	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max
Burned	0.20	0.042	0.12	0.36	0.24	0.038	0.18	0.32	0.16	0.054	0.10	0.36	0.18	0.063	0.13	0.31	0.019	0.017	−0.0022	0.040	0.013	0.028	−0.038	0.050
Unburned	0.19	0.044	0.064	0.27	0.27	0.041	0.20	0.34	0.16	0.045	0.054	0.23	0.24	0.040	0.20	0.33	0.0043	0.022	−0.071	0.037	−0.011	0.017	−0.054	0.0058
On-channel	0.19	0.051	0.064	0.36	0.26	0.046	0.18	0.34	0.16	0.057	0.054	0.36	0.22	0.059	0.13	0.33	0.016	0.016	−0.0072	0.040	0.00084	0.027	−0.042	0.050
Off-channel	0.21	0.023	0.17	0.24	0.24	0.034	0.20	0.32	0.16	0.037	0.11	0.22	0.20	0.063	0.13	0.30	−0.00071	0.026	−0.071	0.040	−0.019	0.018	−0.054	0.013
Single	0.18	0.066	0.064	0.24	0.31	0.041	0.25	0.34	0.13	0.053	0.054	0.19	0.30	0.054	0.20	0.33	0.013	0.038	−0.071	0.028	−0.013	0.036	−0.054	0.050
Upstream	0.20	0.023	0.15	0.23	0.24	0.036	0.22	0.30	0.16	0.039	0.11	0.22	0.20	0.063	0.13	0.29	0.0074	0.017	−0.0072	0.040	0.0055	0.025	−0.029	0.050
Downstream	0.20	0.041	0.15	0.36	0.25	0.039	0.18	0.32	0.16	0.051	0.11	0.36	0.21	0.057	0.13	0.31	0.0078	0.018	−0.019	0.040	−0.0081	0.023	−0.042	0.048
Active	0.19	0.069	0.064	0.27	0.30	0.053	0.21	0.34	0.17	0.064	0.054	0.23	0.29	0.043	0.22	0.33	0.016	0.017	−0.0071	0.037	−0.0043	0.026	−0.042	0.028
Inactive	0.20	0.038	0.12	0.36	0.24	0.040	0.18	0.32	0.16	0.052	0.10	0.36	0.19	0.064	0.13	0.31	0.010	0.024	−0.071	0.040	−0.0053	0.027	−0.054	0.050
BDA	0.16	0.027	0.15	0.21	0.26	0.027	0.22	0.29	0.16	0.016	0.16	0.19	0.22	0.016	0.20	0.25	0.0043	0.0048	−0.0072	0.005	−0.022	0.014	−0.039	0.00084
Recent	0.20	0.040	0.064	0.21	0.26	0.041	0.21	0.34	0.16	0.041	0.054	0.20	0.22	0.051	0.16	0.33	0.0043	0.016	−0.0072	0.040	−0.0043	0.028	−0.039	0.050
Moderate	0.19	0.067	0.12	0.36	0.30	0.046	0.19	0.32	0.18	0.076	0.10	0.36	0.29	0.058	0.15	0.31	0.016	0.012	−0.0013	0.037	−0.0055	0.027	−0.042	0.050
Old	0.21	0.022	0.17	0.24	0.24	0.029	0.18	0.30	0.16	0.034	0.11	0.22	0.19	0.056	0.13	0.29	0.0083	0.028	−0.071	0.040	−0.0091	0.024	−0.054	0.028
All ponds	0.20	0.044	0.064	0.36	0.25	0.042	0.18	0.34	0.16	0.050	0.054	0.36	0.22	0.060	0.13	0.33	0.0078	0.021	−0.071	0.040	−0.0071	0.026	−0.054	0.050
All reaches	0.20	0.043	0.064	0.24	0.25	0.044	0.19	0.34	0.16	0.042	0.054	0.21	0.22	0.057	0.13	0.31	0.0051	0.027	−0.071	0.040	−0.0039	0.029	−0.054	0.050

TABLE 3 Summary of continuous geomorphic characteristics by pond category. The median, standard deviation, minimum, and maximum values for continuous variables are listed for each categorical group, and summarized for all ponds and all reaches.

Category	Geomorphic																							
Variable	Current catchment area, km^2				Historical catchment area, km^2				Catchment slope, percent rise				Relief ratio				Valley width, m				Valley gradient, percent rise			
Group	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max	Med	SD	Min	Max
Burned	3.4	8.2	0.0045	25	4.7	10	1.6	27	19	10	4.7	40	0.13	0.080	0.068	0.43	87	149	43	652	2.1	1.7	0.0000	6.8
Unburned	10	28	0.014	103	27	30	2.3	103	36	6.2	22	45	0.23	0.10	0.087	0.41	150	122	41	394	1.1	2.5	0.0047	7.9
On-channel	10	24	0.004	103	14	23	1.6	103	28	12	4.7	45	0.14	0.079	0.068	0.43	100	147	41	652	2.4	2.3	0.0000	7.9
Off-channel	1.6	4.4	0.014	18	18	27	1.8	82	25	14	8.4	43	0.23	0.12	0.079	0.41	129	125	59	394	1.5	1.1	0.0047	3.4
Single	26	41	0.016	103	54	38	14	103	33	7.6	28	45	0.19	0.11	0.10	0.41	219	93	148	394	0.69	1.0	0.20	2.8
Upstream	2.6	10	0.058	23	16	21	1.6	66	28	10	8.8	39	0.16	0.12	0.085	0.43	86	124	45	394	3.0	2.5	0.82	7.9
Downstream	3.0	7.1	0.0045	23	10	15	1.9	66	23	13	4.7	43	0.15	0.092	0.068	0.39	99	150	41	652	2.0	1.9	0.0000	6.9
Active	25	41	0.10	103	25	39	10.4	103	33	12	16	45	0.15	0.055	0.10	0.24	203	225	41	652	0.69	1.9	0.0000	4.9
Inactive	2.1	7.7	0.0045	25	18	21	1.6	82	23	13	4.7	43	0.16	0.12	0.068	0.43	95	123	43	394	1.8	1.7	0.0047	6.8
BDA	10	5.2	10.2	23	10	5.2	10.2	23	35	2.0	31	37	0.20	0.062	0.087	0.24	110	45	45	181	5.2	2.2	2.43	7.9
Recent	18	29	3.4	103	18	29	3.4	103	34	8.4	19	45	0.14	0.053	0.087	0.24	99	97	41	394	3.5	2.5	0.31	7.9
Moderate	0.40	8.2	0.0045	25	27	23	3.0	66	28	15	4.7	42	0.21	0.13	0.068	0.43	266	145	45	394	1.2	1.4	0.20	4.9
Old	1.9	5.7	0.014	18	4.7	20	1.6	82	22	13	4.7	43	0.16	0.12	0.071	0.41	98	156	43	652	1.8	1.3	0.0000	4.4
All ponds	3.4	21	0.0045	103	16	25	1.6	103	26	13	4.7	45	0.16	0.10	0.068	0.43	117	138	41	652	2.0	2.1	0.0000	7.9
All reaches	11	29	0.016	103	22	32	2.3	103	28	12	4.7	45	0.16	0.082	0.071	0.41	148	158	43	652	1.8	1.9	0.0000	6.3

3.1 | Pond sediment volume

The median volume of sediment stored in 40 individual ponds was 465 m^3 with a range from 4 to 4888 m^3 and a standard deviation of 1014 m^3 (Table 1). Sediment volumes generally related to pond characteristics; however, there was no significant difference in the sediment volumes of burned and unburned ponds (Figure 3). Furthermore, sediment volume did not significantly correlate with catchment burn characteristics or vegetation characteristics. The pond surface area strongly correlated with sediment volume such that larger ponds contained more sediment ($R^2 = 0.60$). Sediment volume also positively correlated with valley width ($R^2 = 0.17$) and negatively with valley gradient ($R^2 = 0.27$).

Off-channel ponds stored a median of 763 m^3 which was significantly more sediment than the median of 241 m^3 stored in on-channel ponds. BDAs ponds stored a median of 12 m^3 of sediment which was significantly less sediment than naturally constructed beaver ponds. Naturally constructed and actively maintained beaver ponds had a median of 306 m^3 of sediment which was not significantly different from the median 628 m^3 stored inactive ponds. Additionally, older ponds stored significantly greater volumes of sediment than recently constructed ponds, with medians of 756 and 79 m^3 respectively, though neither group was significantly different from moderately aged ponds with a median of 416 m^3. The volume of sediment did not significantly differ by the sequential position of the pond along the reach.

3.2 | Reach sediment volume

The median reach sediment storage was 913 m^3 with a range from 6 to 5434 m^3 and a standard deviation of 2010 m^3 (Table 1). Reach sediment storage showed no significant relationship with any of the catchment burn, vegetation, or geomorphic characteristics tested.

3.3 | Normalized pond sediment volume

Pond sediment volume normalized by the current drainage area had a median value of 150 m^3/km^2 and a range from <1 to 56 546 m^3/km^2 and a standard deviation of 15 853 m^3/km^2 (Table 1). Catchment burn characteristics did not significantly relate to normalized sediment volumes. Likewise, burned ponds stored a median of 164 m^3/km^2 of sediment which did not significantly differ from the median of 45 m^3/km^2 of sediment stored in unburned ponds ($p = 0.57$) (Figure 3).

Pre-fire catchment vegetation cover significantly correlated with the normalized sediment volume in a positive direction ($R^2 = 0.23$). The other vegetation metrics did not significantly relate to normalized sediment volume. Of the geomorphic characteristics, relief ratio, valley gradient, and valley width significantly related to normalized sediment volumes. The valley gradient negatively corresponded to normalized sediment volume ($R^2 = 0.33$), whereas a positive relationship was found with the relief ratio ($R^2 = 0.20$) and valley width ($R^2 = 0.22$).

Off-channel ponds stored significantly higher normalized sediment volumes, with a median of 796 m^3/km^2, than on-channel ponds with a median of 41 m^3/km^2. Recently constructed ponds stored a median of 3 m^3/km^2 normalized sediment volume which was significantly less than moderate and old ponds, with medians of 1890 and 462 m^3/km^2 respectively.

3.4 | Normalized reach sediment volume

The median normalized storage for the 17 reaches was 172 m^3/km^2 with a range from <1 to 56 546 m^3/km^2 and standard deviation of 13 706 m^3/km^2 (Table 1). This response metric did not significantly relate to any of the catchment burn or vegetation characteristics, and only one of the geomorphic characteristics. The relief ratio of the catchment exhibited a significant, weak positive relationship with the normalized reach sediment volume ($R^2 = 0.24$).

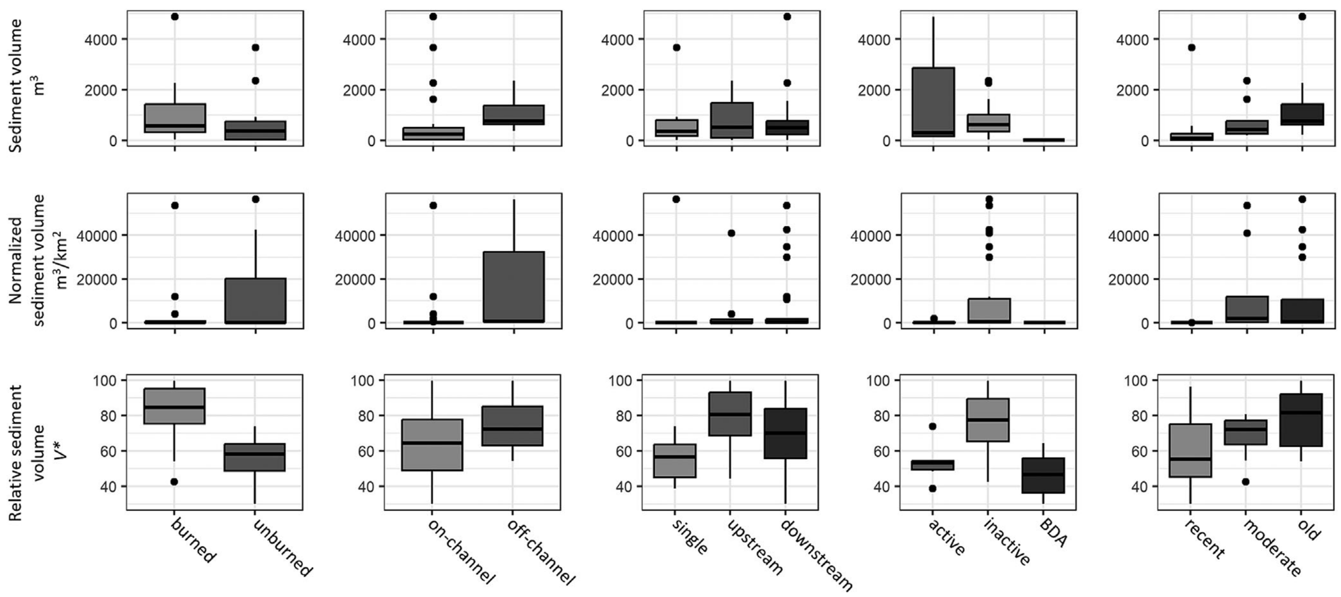

FIGURE 3 Box plots of pairwise analyses of categorical explanatory variables and continuous response variables. The interquartile range is bounded by the box with the median indicated by the middle line and outliers represented by dots. The explanatory variables grouped on the x axes consist of burn status, channel position, reach position, activity, and age category. The response variables consist of sediment volume, sediment volume normalized by drainage area, and relative sediment volume.

3.5 | Relative sediment volume

The median relative volume of sediment in ponds was 70% with a range from 30% to 100% and a standard deviation of 19% (Table 1). Burned ponds stored a median of 85% sediment relative to the total pond volume which significantly exceeded the median of 58% stored in unburned ponds (Figure 3). Catchment burn characteristics did not significantly relate to the relative sediment volume. Local vegetation characteristics were significantly related to the relative sediment volume, while the same characteristics did not demonstrate trends at the catchment scale. Local pre-fire vegetation cover negatively related to relative sediment volume such that more vegetation corresponded to less sediment storage (pseudo-R^2 = 0.08). Local post-fire vegetation cover also negatively correlated (pseudo-R^2 = 0.44). Conversely, the local post-fire vegetation cover positively related to relative sediment volume (pseudo-R^2 = 0.08). Valley width was the only geomorphic characteristic of significance; it negatively corresponded to relative sediment volumes (pseudo-R^2 = 0.09). Finally, the pond surface area also negatively corresponded to relative sediment volumes (pseudo-R^2 = 0.05). Beaver activity significantly related to residual volume: inactive ponds had higher relative sediment volumes compared to active ponds with medians of 77% and 53% respectively.

3.6 | Sedimentation rates

The total sedimentation rate refers to the average rate of sediment accumulation at the cored location since the pond was established. Sediment cores were not collected at three of the 40 ponds included in the analysis of other response variables. Of the remaining 37 ponds, the median sedimentation rate was 3.0 cm/year. The point sedimentation rates exhibited a wide spread with a range of 0.4 to 52.2 cm/year and standard deviation of 9.8 cm/year.

We sampled 21 ponds where both pre- and post-fire sedimentation rates could be estimated from sediment cores. One pond recorded a lower post-fire sedimentation rate compared to the pond's pre-fire rate. This pond was impounded behind a BDA constructed in 2020, and although the upper parts of the catchment burned, the area around the pond did not. Because of the short time frame for calculating both pre- and post-fire sedimentation rates and complicated catchment burn history, this pond was considered an outlier and excluded from the analysis. In the remaining 20 ponds, the median post-fire sedimentation rate of 20.4 cm/year was higher than the pre-fire rate of 1.8 cm/year (Figure 4). The difference in sedimentation rates spans over an order of magnitude and is significant. Post-fire sedimentation rates exhibited more variability with a range of 4.5–25.5 cm/year and standard deviation of 7.4 cm/year, compared to pre-fire rates with a range of 0.6–13.5 cm/year and standard deviation of 2.9 cm/year.

3.7 | Volumetric sediment accumulation rates

The median volume of sediment accumulated per year in ponds was 27 m^3/year. The distribution was right skewed with a standard deviation of 291 and a range from 1 to 1833 m^3/year. The background catchment sediment export rate was higher with a median of 107 m^3/year. It was also right skewed with a standard deviation of 639 m^3/year and range from 1 to 3192 m^3/year. Finally, the median proportion of sediment export from catchments stored in ponds was 40%. It also was strongly right skewed with a large amount of variance as demonstrated by the standard deviation of 2176% and range from 0% to 8651%.

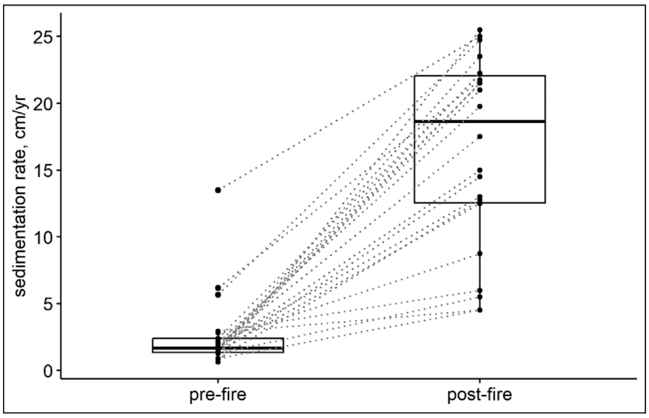

FIGURE 4 Paired comparison of pre- and post-fire sedimentation rates (cm/year) from 20 ponds where pre- and post-fire sediments were present and distinguishable. Paired observations are connected by grey dotted lines showing that post-fire sedimentation is unilaterally higher than pre-fire sedimentation rates. Boxplots show that the post-fire rates are higher and more variable than the pre-fire rates.

4 | DISCUSSION

We evaluated the sediment storage in ponds using three response variables, each of which quantified a different aspect of sediment storage. The sediment volume simply measured the absolute volume of sediment stored, whereas the normalized sediment volume allowed for comparison between ponds located in catchments of different sizes, and the relative sediment volume allowed for comparison of ponds of different sizes. The relative volume of sediment stored in each pond was the only response variable that significantly differed by pond burn status. The finding that burned ponds store higher relative volumes of sediment than unburned ponds partially supported our first hypothesis, though we did not find evidence of any relationship between response variables and the catchment burn extent. We found evidence in support of our second hypothesis: post-fire sedimentation rates significantly exceeded pre-fire rates. Finally, we found significant correlations between pond sediment metrics and potential explanatory variables, partially supporting our third hypothesis.

4.1 | Post-fire sediment storage in beaver ponds

We found that ponds stored high volumes of sediment, with a median of 465 m^3. Ponds often were constructed in series, and we found that reaches stored a median of 913 m^3 of sediment total, suggesting that the presence of more ponds leads to greater sediment attenuation. The median pond normalized sediment storage was 150 m^3/km^2, and the reach normalized median was 173 m^3/km^2. The calculated reach storage should be considered a minimum estimate because many reaches contained ponds that were not measured due to our sampling design.

We did not find evidence to support our hypothesis that burned ponds store greater total volumes to sediment than unburned ponds, likely due to the strong control that pond size exerted on the sediment storage capacity of a pond. However, burned ponds stored significantly greater relative volumes of sediment than unburned ponds. Although we could not distinguish between pre- and post-fire sediment storage volumes, this result implies that ponds effectively captured substantive amounts of post-fire sediment. Field observations corroborated this finding. A pre-fire photo of a pond on Little Beaver Creek showed standing water and wetland vegetation, even though the pond had been abandoned for many years, whereas the same pond was almost entirely full of sediment by 2022 (Figure 5). Pond infilling may alter the physical and biological structure of the pond ecosystem, and the suitability for beaver inhabitation, though we did not examine these pathways in this study. Ponds functioning as headwater sediment sinks may reduce the amount of sediment transported out of the catchment.

We calculated volumetric sediment accumulation rates in order to compare the rate at which ponds stored sediment to the rate of sediment production and export within catchments. We observed a wide degree of variation in sediment storage rates, production rates, and the proportion by which these differed for each pond. Ponds stored a median of 40% of the sediment produced by their catchments at background rates. In many ponds, the proportion exceeded 100%. This complements previous findings that sediment transport and storage occur episodically, in response to various disturbance regimes, resulting in discrepancies between short-term sediment yields and long-term erosion rates (Anderson, Anderson, & Anderson, 2015). Catchment sediment yields are often higher in the years following wildfire (de Dios Benavides-Solorio & MacDonald, 2005; Moody & Martin, 2001; Wagenbrenner, MacDonald, & Rough, 2006). Published post-fire sediment yields vary greatly, likely reflecting both real physical variation in sedimentation rates by region, fire characteristics, and post-fire recovery, as well as methodological biases and assumptions (Kirchner, 2001). Our method of calculating volumetric sediment accumulation rates was limited by our inability to contrast pre-fire sediment volumes with post-fire volumes.

Our findings are consistent with previous research documenting high volumes of sediment storage in beaver ponds across a variety of landscapes, signifying that beaver ponds may function as sediment sinks (Larsen, Larsen, & Lane, 2021). A study of small ponds in headwater catchments demonstrated that depending on the spatial position of ponds within the river system, ponds exerted a dominant influence on sediment and nutrient retention in headwater catchments (Schmadel et al., 2019), and beaver ponds may have a similar influence. Furthermore, beaver ponds studied in Poland demonstrated very high trap efficiency in a catchment with large fluxes of silt-sized sediments, implying that beaver ponds are capable of attenuating substantial portions of sediment traveling through a river reach (Giriat, Gorczyca, & Sobucki, 2016).

Importantly, individual beaver ponds and pond complexes stored larger volumes of sediment than hillslope retention structures such as contour-felled logs. This is likely due to simple geometry: beaver dams were typically wider and taller than hillslope structures, and ponds were situated in wide low-gradient valleys (Wagenbrenner, MacDonald, & Rough, 2006). Conversely, ponds had lower storage capacities than engineered water supply reservoirs, which are characterized by large surface areas and deep, oftentimes dredged, basins (Eidmann et al., 2022; Moody & Martin, 2001; Rathburn, Shahverdian, & Ryan, 2018).

Our study centred on one form of disturbance: wildfire. However, the sediment regimes of the ponds may be influenced by multiple intersecting and cascading disturbances such as flooding following fire. Human disturbances may also cause substantial alteration to sediment regimes, including post-fire restoration activities, grazing, timber harvest, road development, and hydrologic diversions. More research is needed to determine the pathways and feedbacks between beaver ponds and multiple forms of disturbance.

4.2 | Sedimentation rates in beaver ponds

The median total sedimentation rate of the ponds (3.0 cm/year), calculated from sediment cores, fell within the range of previously published data (0.2–45 cm/year) (Larsen, Larsen, & Lane, 2021). However, the total sedimentation rate of one beaver pond exceeded published rates at 52.2 cm/year. Like other authors, we documented a large

FIGURE 5 View of abandoned beaver pond (LBC-4) on Little Beaver Creek before and after the Cameron Peak fire. Stars mark matching trees to aid comparison. Left: in June of 2020 (pre-fire), the pond is shallow but has a wide extent of standing water and wetland vegetation. Right: after the fire, by July of 2022 the pond had filled in with dark, charcoal-rich sediment with little standing water remaining. Vegetation type shifted to dense grasses and sedges in the valley floor, contrasting the blackened hillslopes which had yet to recover. [Color figure can be viewed at wileyonlinelibrary.com]

variation in sedimentation rates (Butler & Malanson, 1995; Puttock et al., 2018). The variation in rates may be partially explained by the observed wide variation of sediment thickness within ponds; repeat bathymetric surveys might better capture pond-wide sedimentation trends.

Wildfire disturbance temporarily increased sedimentation rates in ponds. We found that post-fire sedimentation rates were higher than total sedimentation rates and fell within the high end of the published literature for beaver ponds, with a median of 19.8 cm/year. Furthermore, post-fire sedimentation rates were an order of magnitude higher than pre-fire rates, supporting our second hypothesis. Wildfire increased the rate at which ponds fill, potentially countering incision and reconnecting floodplains, but also potentially shortening the lifespan of engineered structures with a limited sediment capacity. Ponds that fill to the brim with sediment cease to function as ponds, causing a shift in habitat availability. Additional research is needed to determine how long it takes for sedimentation to return to pre-fire levels.

4.3 | Additional factors influencing sediment storage

Pond sediment dynamics are shaped by nested contexts. Geology, climate, and ecology are well established as high-level regional drivers of sediment dynamics and processes within rivers (Wohl, 2018; Wohl et al., 2020), and we found evidence that they contributed to pond sediment dynamics.

Local vegetation metrics explained trends in the relative volume of sediment; no other response variables were significantly correlated with either local or catchment scale vegetation metrics. This finding suggests that vegetation in the area immediately surrounding a pond related to how sediment was delivered and stored in the pond. Vegetation loss on nearby hillslopes may have increased sediment delivery to ponds while vegetation in the valley bottom might have increased roughness and resulted in more sediment trapping across the floodplain rather than just in the pond (Bywater-Reyes et al., 2022). Roots may have also stabilized alluvium, so that it was less likely to be reworked during high flows. We found that the area within 200 m of ponds had higher NDVI values than surrounding areas both before and after wildfire. The low magnitude of post-fire vegetation recovery in these areas indicated that these areas remained green following fire. This corroborates the findings of Fairfax & Whittle (2020), who documented more rapid post-fire vegetation recovery in valley floors with beaver ponds; beaver dammed valley floors were also more resistant to fire (Fairfax et al., 2024). The authors attributed the vegetation recovery to lower severity of fire in areas with abundant surface water, and high water tables facilitating rapid regrowth of riparian species. In addition to stabilizing sediments, riparian vegetation may provide forage and materials allowing for beavers to reestablish in a burned area and continue their pond building activities with subsequent impacts on sediment dynamics. Thus, looking beyond the perimeters of open water may illuminate important biogeomorphic feedback pathways influenced by ponds.

We found that various geomorphic characteristics correlated with response variables, suggesting an interplay between processes of sediment production, transport, and deposition, as well as dam structural stability. Wider valleys correlated positively with higher sediment volumes, normalized sediment volumes, and relative sediment volumes. Wide valleys may accommodate higher degrees of channel splitting and avulsion, leaving ponds protected from high velocity zones and prone to sediment infilling. Additionally, the relief ratio of the catchment positively related to the normalized sediment volume of both ponds and reaches. Catchments with higher relief ratios may have steeper first order tributaries, which carry higher sediment loads to ponds. Conversely, steeper valley gradients correlated with lower sediment volumes and lower normalized sediment volume. The higher stream power associated with steep reaches might have caused dams to overtop more readily, become more permeable, or breach entirely. Impounded sediments may have scoured during higher flow events or partial dam breaches, reducing the overall storage.

Pond characteristics interacted with the geomorphic and ecological context to determine sediment fate. Pond surface area strongly corresponded to all three measures of pond sediment volume: larger ponds stored more sediment. Beavers built and maintained dams that impounded larger ponds than BDAs. We found that active beaver ponds and BDAs stored less sediment and had lower relative volumes of sediment than abandoned beaver ponds, which may have been due to the intentional placement of BDAs on 'degraded' channel reaches that were experiencing incision and high sediment fluxes, where habitat was suboptimal for beaver (Nash et al., 2021). In contrast, many of the abandoned ponds were constructed across tributaries with small drainage areas and relatively narrow valley bottoms. The low stream power in these systems may have allowed dams to persist for longer than on larger or incised streams, accumulating large volumes of sediment (Persico & Meyer, 2009). There has been relatively little research quantifying the function and effects of abandoned beaver ponds for sediment storage, although there is evidence that beaver berms (vegetated relict dams) trap large wood, secondarily increasing backwater sediment storage (Wohl et al., 2022).

Older ponds stored higher total and normalized volumes of sediment which is consistent with previous research, indicating that the processes governing sedimentation shift as ponds age (Bigler, Butler, & Dixon, 2001; Butler & Malanson, 1995). Sediment volumes may be influenced by processes of sediment delivery, sediment compaction, and sediment retention in ponds. Beavers are ambitious dam builders and over time are likely to construct ponds upstream, which may decrease the sediment supply to downstream ponds (Johnson-Bice et al., 2022; Puttock et al., 2018). Beavers may use sediments excavated from their ponds to seal their dams, resulting in fine particles being washed downstream; they also excavate canals to maintain swimming space as sediment infilling occurs (Grudzinski, Cummins, & Vang, 2020; Hood & Larson, 2015). Loading may induce compaction of sediments resulting in lower sediment volumes, and greater sediment density. The likelihood of a pond experiencing a high flow increases as it grows older, creating more opportunities for dam breaches and partial sediment scour.

Off-channel ponds stored greater sediment volumes, normalized sediment volumes, and relative sediment volumes than on-channel ponds. Dams may force avulsion and enhance multithread planforms, stranding ponds off the channel and decreasing sediment supply to the pond, while increasing the stability of sediments already in place (John & Klein, 2004; Polvi & Wohl, 2013).

Although other studies have quantified beaver pond sediment thickness (Bigler, Butler, & Dixon, 2001; Butler & Malanson, 1995), to our knowledge, only one study has used relative sediment volume to compare the proportional sediment storage between ponds and it comes from a single stream reach in the United Kingdom (Puttock et al., 2018). The authors documented less (44.3% *V**) relative sediment storage across that pond complex than overall median we found at our sites (70% *V**). However, ponds in our study with similar characteristics to those in the UK also had closer relative sediment volumes. The similar ponds included those that were unburned (58% *V**), actively inhabited (53% *V**), and recently constructed (55%- *V**). The BDAs in our study most closely resembled the relative volumes documented in the UK with 47% *V**. Together, these results suggest that beaver maintenance activity was critical for sustaining pond storage; they filled with sediment as they aged and were abandoned. Ponds of varied characteristics provided post-fire sediment storage, thereby reducing the amount of sediment transported downstream.

5 | CONCLUSIONS

This study shows that beaver ponds and BDAs capture post-fire sediment at high rates and that pond and catchment characteristics relate to the amount of sediment stored. Sediment surveys and sediment cores from a large number of beaver ponds and BDAs allowed for an analysis sediment volumes and sedimentation rates in ponds. We found no significant difference between the volume of sediment stored ponds in burned areas compared to unburned ponds; however, burned ponds stored higher relative volumes of sediment. Sediment volume strongly correlated with the pond surface area. Additionally, older ponds and natural ponds not currently inhabited by beaver stored higher volumes of sediment compared to younger ponds and ponds actively maintained by beaver. Furthermore, we found that in ponds with both pre- and post-fire sediments, sedimentation rates were an order of magnitude higher after fire. Our work demonstrates that beaver ponds accumulate and store post-fire sediment, sediment that is often detrimental to downstream ecosystems including human communities. Pond and catchment characteristics related to how much sediment was stored in ponds. This research can inform sediment and fire mitigation strategies, as well as beaverbased restoration planning in fire-prone landscapes.

AUTHOR CONTRIBUTIONS

SBD, SLR, and EW conceptualized the research and developed the methodology. SBD and SLR acquired funding. SBD conducted the fieldwork with supervision from SLR, and SBD wrote the initial draft. SLR and EW provided reviews and editing.

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DATA AVAILABILITY STATEMENT

Data are available at 10.5061/dryad.xsj3tx9p4. Requests for code or intermediate data will be provided by SBD upon reasonable request.

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