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Fine Sediment Depositional Patterns and Fish Habitat Following Wildfire and Debris Flow

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ABSTRACT

The 2020 Cameron Peak wildfire burned part of the Poudre River catchment in Colorado, USA. The river flows through a high-gradient canyon before entering a lower-gradient transition zone with modified channel morphology and flow regime. Widespread post-fire erosion introduced fine sediment (<2 mm) to the river, causing sediment deposition and a major fish kill. Fine sediment deposition in the transition zone partially blocked or filled fish habitat in channel margin backwaters and side channels and filled interstices in fish-spawning habitat along the cobble-boulder bed channel. During summer 2023, we quantified fine sediment retention at 18 sites along the river by measuring fine sediment volumes and embeddedness. Our objectives were to (i) evaluate whether reach-scale geomorphic attributes or river distance downstream from the sediment source correlate more strongly with reach-scale fine sediment volume and embeddedness and (ii) use 2D hydraulic modeling and incipient motion equations to estimate the discharge necessary to mobilize the channel bed and remove excess fine sediment. Reach location (canyon vs. transition zone) best explained the volume of fine sediment and embeddedness, although the reach-scale variables of gradient and cross-sectional area were significant predictors of fine sediment retention. Hydraulic modeling indicated that a 2-year return interval flow mobilizes a substantial portion of the bed at the canyon site, whereas bed mobilization requires a 5- to 10-year flow at the transition zone sites. Management to mitigate post-fire sedimentation and stressors to fishes may need to emphasize changes in river corridor geometry where consumptive water use limits flushing flows.

1 | Introduction

Increases in water, sediment, and other materials entering river corridors after wildfire are well documented in the western United States and other fire-prone regions (Abatzoglou and Williams 2016; Richardson et al. 2022; Ortega-Becerril et al. 2024; Ridgway et al. 2024). Increased water and sediment yields typically are greatest in the first 3–10 years following fire, until upland ground cover regrows and stabilizes hillslopes (Shakesby and Doerr 2006; Shakesby 2011; Rengers et al. 2020;

Graber et al. 2023). The effects on river corridors of increased water and sediment inputs depend on factors such as (i) the magnitude and duration of the increase (Smith et al. 2011; Paul et al. 2022), especially relative to transport capacity and erosional resistance of the river corridor (Eaton et al. 2010; Murphy et al. 2019; Nyman et al. 2020); (ii) the source of the sediment (uplands vs. channel erosion) (DeLong et al. 2018; Guilingier et al. 2020; Rengers et al. 2021); (iii) the hydroclimatic conditions in the years immediately after the fire (Moody et al. 2013); (iv) the biogeomorphic heterogeneity and resilience of the river

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corridor (Wohl et al. 2022; Triantafyllou and Wohl 2024); and (v) the recent history of fires and floods in the catchment (e.g., Hooke 2015; Mao 2018).

The effects of increased post-fire water and sediment fluxes on stream biota, including biofilms, benthic macroinvertebrates, and fishes, are also quite variable, depending on the physical response of the river corridor but also on factors such as connectivity and the presence of refugia during disturbances (Townsend and Hildrew 1994; Whitney et al. 2017) and the rate of recovery of riparian vegetation as this influences shading, stream temperature, and organic matter inputs (Pettit and Naiman 2007). Although wildfire is a natural, recurring disturbance in many regions, changing climate, land use, and a history of fire suppression that has altered wildland fuels are causing pronounced changes in wildfire frequency, spatial extent, and severity in the western United States (Burke et al. 2021). This, combined with extensive human alterations to river networks, including altered flow regimes and reduced connectivity, may be reducing the ability of river ecosystems to recover following wildfire.

We present a case study of post-fire changes in fish habitat along the Poudre River in Colorado, USA. The Poudre River was affected by a 2020 wildfire, followed by a large debris flow from the tributary Black Hollow Creek in 2021. The Poudre River exemplifies many of the challenges for river ecosystems in the western United States and in other fire-prone regions of the world. The river heads in the Southern Rocky Mountains, a forested region that has experienced multiple large, high-intensity wildfires during the past four decades (Hawbaker et al. 2023). Although the river corridor in the mountains is modified by flow regulation, roads, and local land uses, it is relatively natural compared to the river corridor in the transition zone, which is subject to extensive flow regulation, channelization, altered land cover for agriculture and urbanization, and disrupted connectivity associated with culverts, grade-control structures, irrigation intakes, and other infrastructure (City of Fort Collins 2017; Bestgen et al. 2020). Under these conditions, post-fire changes in channel morphology may be limiting the continued survival of native fishes (Jager et al. 2021). Although we present a case study here, the post-fire changes in the river corridor and associated threats to continued fish persistence, as well as the methods that we used to assess post-fire sedimentation and effects on fish habitat, should be widely applicable to other river corridors affected by wildfire.

We had two primary objectives. The first objective was to examine the physical conditions that facilitate fine sediment (<2 mm) retention in the bankfull channel of the Poudre River and specifically to evaluate whether reach-scale geomorphic attributes or distance downstream from the primary sediment source at the Black Hollow confluence better predict fine sediment retention. The second objective was to estimate the discharge required to remobilize and remove excess fine sediment in four reaches distributed along the Poudre River downstream from Black Hollow. Although quantitative, our estimates of sediment mobilization represent approximations because of the methods used to assess bed-grain size characteristics and critical shear stress.

2 | Study Area

The Poudre River heads in the Southern Rocky Mountains at 4145 m elevation and flows eastward approximately 200 km to join the South Platte River on the Great Plains at 1399 m elevation, draining 4895 km² (Figure 1). The mountainous portion of the catchment is underlain by Precambrian-aged crystalline rocks, and the channel is either bedrock or boulder-bedded (~500 to >2050 mm diameter). Snowmelt dominates annual peak flow at elevations above 2300 m, and unit peak discharge seldom exceeds 1.1 m³/s/km² (Jarrett 1990). Upland vegetation includes tundra (>3460 m elevation), subalpine conifer forest (3360–2850 m elevation), and montane conifer forest (2850–1835 m elevation). Climate is semiarid, with increasing mean annual temperature (−4°C to 10°C) and decreasing mean annual precipitation (1000 to 530 mm) at lower elevations. We designate study reaches in the mountainous portion of the Poudre River as canyon sites.

The Poudre River enters the transition zone at ~1565 m elevation ~60 km downstream from the confluence with Black Hollow. This portion of the catchment is underlain by tilted Pennsylvanian- through Cretaceous-aged sedimentary rocks in the foothills and Quaternary alluvium on the Great Plains. The channel bed in the transition-zone portion of the catchment is predominantly cobble to small-boulder-sized (~60–260 mm diameter) sediment. Although annual snowmelt peak flow occurs, the lower elevation tributaries (<2300 m elevation) can also experience flash floods from summer convective storms. These floods can have unit peak discharge up to 40 m³/s/km² (Jarrett 1990), although the unit peak discharge declines in larger rivers such as the Poudre River mainstem. Upland vegetation in the transition zone is primarily short-grass prairie, with cottonwood forests historically present along river corridors. Climate is semiarid, with 380 mm mean annual precipitation (NOAA 2024). The Poudre River in the transition zone historically had multithread, sinuous channels with broad floodplains, but the river has been confined to a laterally constrained, less sinuous single channel since settlement by people of European descent starting in the 1860s (Sexton 1998; Shanahan et al. 2014; Bestgen et al. 2020). Although no major dams are present along the mainstem, numerous diversions reduce peak and base flow by 59% and 57%, respectively, from pre-development levels (Shanahan et al. 2014).

The transition zone along the Poudre River spans the gradient between cold, trout-dominated waters in the mountains and a mixed temperature regime with cool and warmwater plains fishes downstream; the transition zone is the westernmost extent of many Great Plains fishes (Fausch and Bestgen 1997). Native fish species diversity, distribution, and abundance have declined since the 1990s, partially due to flow diversions and increased presence of non-native brown trout (*Salmo trutta*) (Haworth and Bestgen 2024). We designate study reaches in this portion of the Poudre River as transition zone sites.

The 2020 Cameron Peak wildfire burned over 840 km², including 558 km² in the mountainous portion of the Poudre River catchment. The fire was likely human-caused and burned subalpine forests that experience wildfire infrequently. The

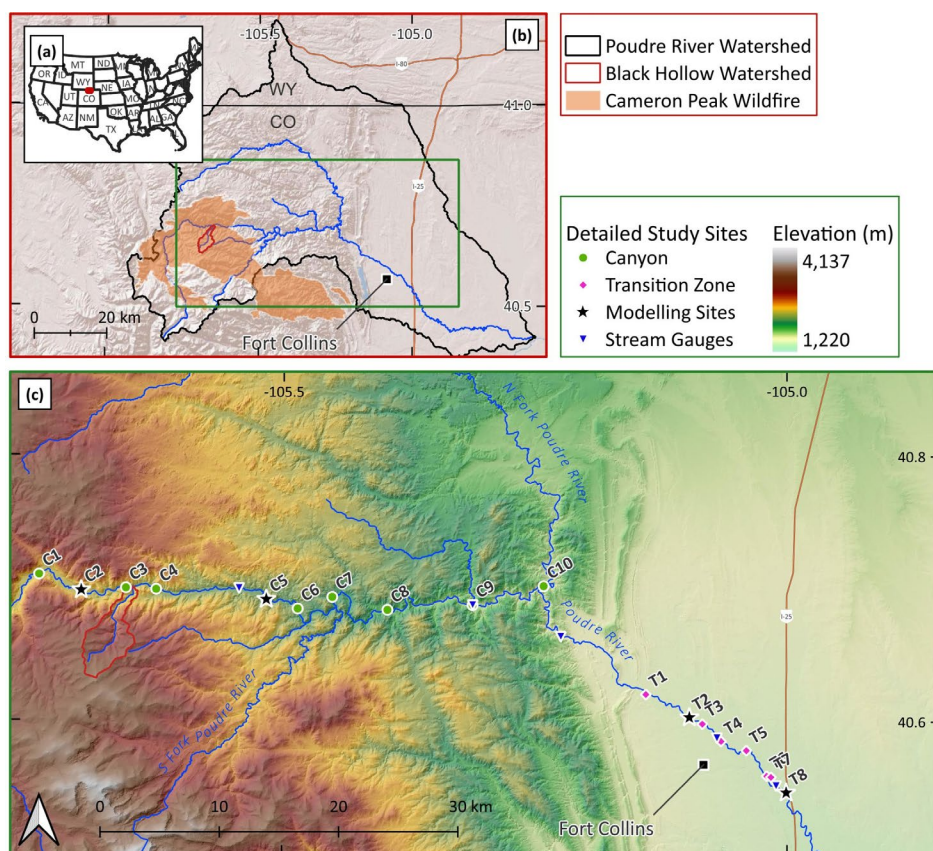


FIGURE 1 | Location map of study area, showing Poudre River catchment, location of Black Hollow subcatchment in red outline, study reaches (C = canyon sites 1–10, T = transition sites 1–8), and stream gauges. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/raa.7064)]

2020 burned area included 30% burned at moderate severity and 6% at high severity (BAER 2020). Ninety percent of the Black Hollow catchment burned during the 2020 wildfire (M. Fairchild, Arapaho-Roosevelt National Forest, pers. comm., 2021). On 20 July 2021, a convective storm over the burn scar triggered a debris flow in Black Hollow Creek that resulted in four fatalities and deposited substantial amounts of sediment, ash, and large wood in a debris fan at the confluence with the Poudre River, as well as along 100 km of the mainstem Poudre River (Waskiewicz et al. 2022). Toxic levels of suspended sediment and ash in the Poudre River reduced oxygen levels, leading to a massive fish kill. Sampling after the debris flow by Colorado Parks and Wildlife indicated a complete loss of the fishery for the first 32 km downstream from Black Hollow, with continuing impacts to the fishery, including sedimentation, extending 95 km downstream (K. Battige, Colorado Parks and Wildlife, pers. comm., 2022). The pulse of sediment required the City of Fort Collins, along the mainstem Poudre River, to shut down water intakes on the river, and elevated turbidity levels continued to pose threats to water treatment for several weeks after the debris flow (Heath and Thorp 2023).

Although peak discharge on the Poudre River caused by the Black Hollow debris flow attenuated substantially downstream (Figure S1), the flow retained sufficient transport capacity to cause extensive fine (<2 mm diameter) sediment deposition along the entire length of the river in the transition zone. Visual observations by fish biologists suggested that snowmelt peak

flows in 2022 removed much of the very fine (silt- and clay-sized) sediment exposed at the surface in the active channel, but sand was retained. Depositional areas, such as backwaters and sites upstream from diversion dams, continued to accumulate sand even as high flows receded. We conducted the sampling described here during the summer of 2023, following 2 years of snowmelt peak flows (2022, 2023 runoff seasons) after the 2021 debris flow.

3 | Methods

3.1 | Characterization of Fine Sediment Retention

Our first objective was to evaluate the relative importance of reach-scale geomorphic attributes versus distance downstream from the primary sediment source as controls on fine sediment retention. We chose 18 study sites, 16 of which overlapped with existing monitoring sites for fish populations maintained by Colorado Parks & Wildlife (canyon sites) and Colorado State University (transition zone sites; Haworth and Bestgen 2024). We added 2 canyon sites in portions of the river corridor that were not covered by the fish monitoring sites to more fully represent the range of valley geometry in the canyon.

Study reaches were typically 300-m long and included several habitat units (e.g., riffle, run, pool). We quantified fine sediment retention using (i) volumetric surveys of measurable fine sediment deposits and (ii) substrate embeddedness surveys. Volumetric

surveys included only deposits below bankfull stage and only deposits with one planar dimension ≥ 5 m long. We differentiated sediment deposited after the Black Hollow debris flow from earlier deposition based on the presence of woody vegetation growing on the deposits (pre-debris flow) and the presence of ash and charcoal in the sediment (post-debris flow). We derived volume from measurements of deposit-surface length, deposit-surface width at 10 evenly spaced transects, and from 3 depth measurements at 25%, 50%, and 75% along each transect. Depth was measured with a metal rod inserted to refusal by a cobble/boulder layer or a pre-existing layer of fine sediment. We expressed the volume of fine sediment as a ratio using the bankfull volume of each reach (fine sediment volume (m^3)/bankfull volume (m^3)).

We modified the US Environmental Protection Agency's Monitoring and Assessment Protocol (Peck et al. 2001) for substrate embeddedness to correspond to pre-fire measurements made by fish biologists at the study sites. We visually estimated substrate embeddedness at 5 evenly spaced points along cross-channel transects, with transects spaced at 30-m intervals downstream (one-tenth of total reach length) along the reach. We quantified embeddedness into quartile percentages (0%, 25%, 50%, 75%, 100%) based on visual inspection of individual large grains at each sample point along the transect. Embeddedness of 25%, for example, indicates that 25% of an individual coarse grain is surrounded by fine sediment. Averages were calculated from the five measurements for each transect and the 50 measurements for each study reach.

We quantified reach-scale geomorphic attributes from field measurements of channel gradient, bankfull channel dimensions, channel cross-sectional geometry, bank length ratio, and streambed grain-size distribution. We quantified the distance downstream from the primary sediment source using the QChainage tool in QGIS (version 3.26.3). We measured cross-sectional geometry using a set of Emlid Reach RS2 RTK GPS receivers at sites where these had sufficient satellite connectivity and processed the data using NOAA Continuously Operating Reference Stations (CORS) correction and Emlid Flow software. This system could not receive signals in some of the canyon reaches, so we used an auto-level and stadia rod for cross-sectional surveys at these sites. We used Cross Section Viewer (Shelley and Bailey 2018) to process cross-sectional survey data and derive bankfull hydraulic radius and bankfull width/depth ratio for each transect. Transect values were then averaged for each study reach.

Bank length ratio was the ratio of the total bank length to the centerline length in a given reach (Polvi et al. 2014). A channel with straight banks will have a value of 2, and irregular banks will create higher values. We included the outer banks and bank lengths of islands in the numerator.

Sediment grain-size distribution was visually estimated at the 5 evenly spaced points along each transect used for embeddedness, following the EPA protocol. To maintain continuity with years of fish habitat surveys, we grouped sediment size into classes and listed these in order of decreasing abundance. Sediment classes included fines (< 0.06 mm), sand (0.06–2 mm), gravel (2–64 mm), small cobble (65–128 mm), large cobble (129–256 mm), and boulders (> 256 mm). Values at each point included up to three sediment classes, listed by primary, secondary, and

tertiary abundance. These data were then averaged using the central value of each class to yield 55 values per study reach. The median grain size (D_{50}) was calculated from those values.

We used the field transects to categorize dominant channel units at the transect (riffle, run, pool, side channel, or backwater). Side channels are smaller channels separated from the primary channel by an area above bankfull stage and are inundated for some portion of each year. Backwaters are channel-margin irregularities with flow separation and low velocity. Backwaters are usually inundated at low flows and have surface hydrologic connectivity with the main channel. Differentiation of channel units facilitated the analysis of fine sediment retention in relation to channel-unit type.

3.2 | Estimation of Fine Sediment Remobilization

Our second objective was to estimate the discharge required to remobilize and remove excess fine sediment in four reaches distributed along the river and representative of different valley morphologies. These included 1 canyon site upstream from the Black Hollow confluence, 1 canyon site downstream from Black Hollow, and 2 transition zone sites. We used the HEC-RAS 2D hydraulic model and simple incipient motion equations. The four modeled reaches represented the range of geomorphic settings, flow regimes, and distances from the sediment source. At each reach, we compared the extent of bed mobilization for the 2-, 5-, and 10-year return interval flows. We inferred bed mobilization based on exceedance of the median-diameter bed-surface grain size at each reach.

For the two canyon reaches, we combined bathymetric RTK surveys with 1-m resolution lidar from the USGS 3DEP website into a single DEM for each reach. This 2013 lidar adequately represented above-water topography at these reaches, but was not appropriate for the transition-zone reaches, where the channel has changed substantially since 2013. At the two transition zone reaches, we used drone surveys (Parrot ANAFI Ai drone) to obtain aerial images processed using Agisoft Metashape (version 1.5.2) software, along with bathymetric RTK surveys, to create DEMs.

We estimated flood return intervals at the four sites used for hydraulic modeling. Return interval estimates came from stream gauge data close to the transition-zone reaches and from the US Geological Survey StreamStats routine (U.S. Geological Survey 2019) for the canyon reaches, which do not have nearby stream gauges. We estimated bed-sediment entrainment thresholds for the D_{50} grain size at each reach using the critical Shields parameter (Shields 1936) and values listed in Julien (2010, Table 7.1). We assumed that bed substrate must be mobilized to effectively entrain the fine sediment that embeds the coarser material (Kondolf and Wilcock 1996), but our approach to estimating interstitial fine sediment mobilization likely represented a first-order approximation because of the use of reach-averaged values and the inherent uncertainties associated with the mobilization of coarse bed sediment (Komar 1987; Powell 1998; Hodge et al. 2024; Vázquez-Tarrio et al. 2024). Our intent here was to estimate the flows needed to entrain the less readily mobilized interstitial sand, rather than the exposed deposits of sand on top of the pre-fire streambed.

TABLE 1 | Characteristics of study reaches.

Reach ^a	Dr A ^b (km ²)	Distance ^c (km)	Bed S ^d (m/m)	WS ^e (m/m)	Bf XSA ^f (m ²)	Bf W/ D ^g (m/m)	BL ratio ^h (m/m)	Fine sed vol ⁱ (m ³)	Fine sed vol ratio ^j (m ³ /m ³)	Embed ^k (%)
C1	451	−10.0	0.0032	0.0024	31.4	39.1	3.12	232	0.0259	56.4
C2 ^l	508	−5.0	0.0050	0.0028	28.5	36.2	2.06	52	0.0062	55.5
C3	534	−0.6	0.0111	0.0133	21.6	33.2	2.07	70	0.0115	52.5
C4	557	1.8	0.0128	0.0128	23.5	30.6	2.01	133	0.0194	43.5
C5 ^l	632	12.9	0.0086	0.0086	24.9	39.6	2.93	128	0.0167	54.1
C6	648	16.6	0.0076	0.0086	31.1	42.5	3.22	59	0.0063	43.3
C7	964	23.0	0.0092	0.0102	27.3	67.1	3.22	77	0.0088	37.3
C8	1085	31.6	0.0098	0.0097	28.6	31.0	2.01	21	0.0025	42.8
C9	1163	41.8	0.0055	0.0086	25.6	51.5	2.23	66	0.0085	45.0
C10	1254	51.0	0.0070	0.0094	20.8	20.8	2.00	5	0.0008	30.5
TZ1	2875	68.7	0.0068	0.0062	28.7	34.6	3.25	100	0.0123	53.8
TZ2 ^l	2901	73.7	0.0059	0.0054	22.6	30.1	2.04	100	0.0136	61.3
TZ3	2927	75.0	0.0016	0.0026	30.8	30.9	2.10	367	0.0412	58.0
TZ4	2940	77.5	0.0013	0.0024	19.9	21.7	2.65	886	0.1376	56.8
TZ5	2953	80.6	0.0052	0.0025	27.4	24.8	2.48	521	0.0525	56.0
TZ6	3212	84.0	0.0017	0.0012	32.6	23.9	2.50	362	0.0514	88.1
TZ7	3225	84.5	0.0058	0.0062	33.9	53.0	3.03	394	0.0445	48.0
TZ8 ^l	3963	86.9	0.0012	0.0012	42.0	22.5	2.87	592	0.0475	71.5

^aC indicates reach in canyon; TZ indicates reach in transition zone.^bDrainage area.^cDistance downstream from Black Hollow.^dChannel bed gradient.^eWater surface gradient at base flow.^fBankfull cross-sectional area.^gBankfull width/depth ratio.^hBank length ratio.ⁱFine sediment volume.^jFine sediment volume per bankfull volume.^kEmbeddedness.^lIndicates hydraulic modeling reach.

We estimated the magnitude and spatial distribution of bed shear stress using the 2D hydraulic model HEC-RAS, version 6.4.1 (U.S. Army Corps of Engineers 2023), with the terrain surfaces generated as described above. We ran an unsteady flow model with a stepped hydrograph and a 1-s computational interval to keep the Courant numbers below 5. Manning's n roughness values were calibrated at low flows to water-surface elevations at the time of the field surveys. Channel computational cells were 2×2 m for the 2 canyon reaches and 1×1 m for the transition-zone reaches. Floodplain cells were 4×4 m for all reaches. We used RAS Mapper to add a shear stress output (in Pa) from each hydrograph step and exported these as raster files. We used the raster calculator in QGIS to convert the original raster file into dimensionless shear stress units and filtered values greater than or equal to the dimensionless critical shear stress at each reach to determine the portion of the bed likely to experience sediment mobilization. The Raster Layer Zonal

Statistics tool was used to quantify the proportion of channel area exceeding critical shear stress.

3.3 | Statistical Analyses

We used R Statistical Software (version 4.2.2; R Core Team 2021) for all statistical analyses. Fine sediment volume and embeddedness were log transformed to achieve normal distributions. Predictor variables were evaluated using linear regression (Tables S1 and S2) with the *dredge* function from the MuMIn package (version 1.47.5; Barton 2023), which ranks every possible model based on corrected Akaike's information criterion (AIC_c ; corrected for smaller sample size). Reach location was a categorical variable (upstream of Black Hollow, canyon, or transition zone), and we used ANOVA to test $\log_{10}$ (sediment volume) as a function of reach location. Reach-scale predictor variables

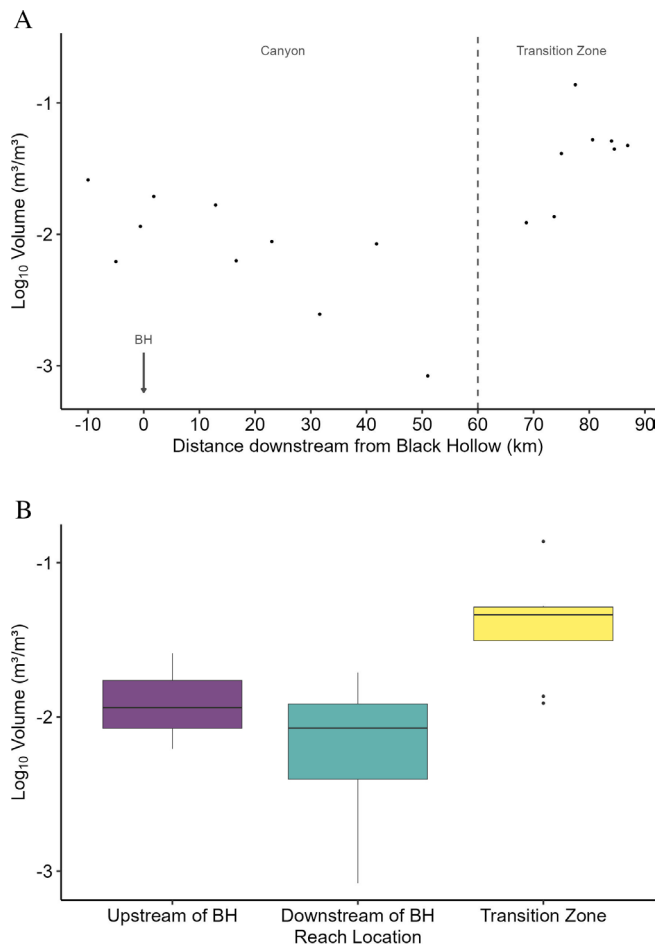


FIGURE 2 | (A) Plot of $\log_{10} \times$ fine sediment volume (expressed as fine sediment volume (m^3)/bankfull volume (m^3)) as a function of distance downstream. (B) Plot of $\log_{10} \times$ fine sediment volume as a function of reach location. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

tested included reach location, bed gradient, bankfull width/depth ratio, bankfull cross-sectional area, and bank length ratio. Fine sediment volume was averaged for each reach; embeddedness was averaged for each transect and for each reach. Predictor variables for embeddedness thus also included habitat unit for the transect-based analyses; this was analyzed with a mixed-effect linear regression model with channel unit as a fixed effect and reach as a random effect using the *lme4* function from the *lmerTest* package (Kuznetsova et al. 2017). We then conducted an ANOVA Type II test and pairwise comparisons between each channel unit using Tukey-adjusted *p*-values.

4 | Results

Basic characteristics of all study reaches are summarized in Table 1.

4.1 | Controls on Fine Sediment Retention

Reach location was a better predictor of fine sediment volume (ANOVA, $p=0.005$) and embeddedness (ANOVA Type II test,

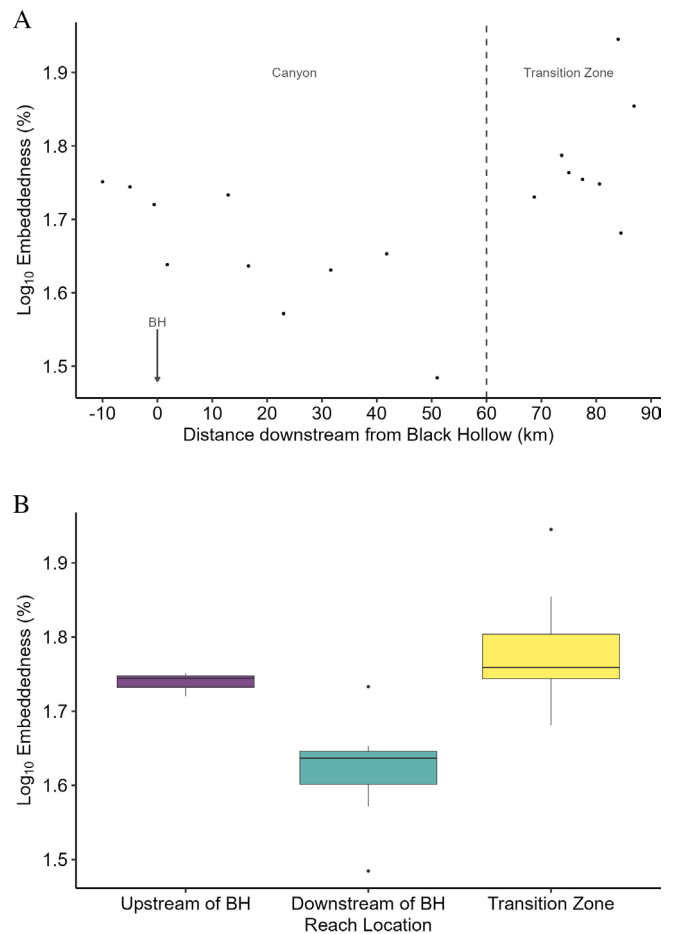


FIGURE 3 | (A) Plot of $\log_{10}(\text{embeddedness})$ as a function of distance downstream (B) Plot of $\log_{10}(\text{embeddedness})$ as a function of reach location. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

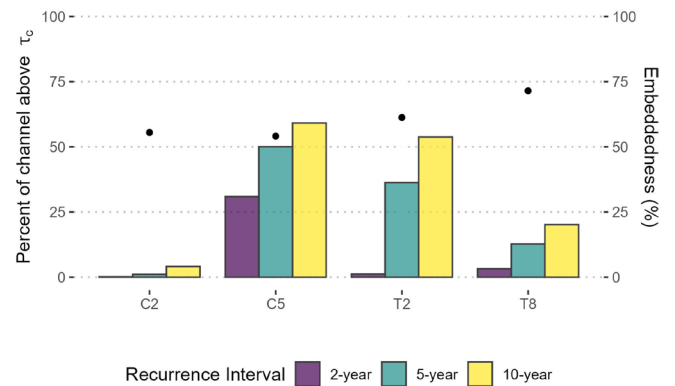


FIGURE 4 | Proportion of channel above critical shear stress for each return interval flow at each of the four modeled reaches. Embeddedness at each reach is indicated by black dot with value on right y-axis. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

$p=0.003$) than reach-scale geomorphic attributes. Some reach-scale variables correlated significantly with sediment variables; however, gradient was inversely correlated with fine sediment volume ($R^2=0.37$, $p=0.008$). Fine sediment volume decreased with distance downstream until the transition zone, where fine sediment volume increased rapidly (Figure 2A). Pairwise comparisons of estimated means indicated transition zone sizes had

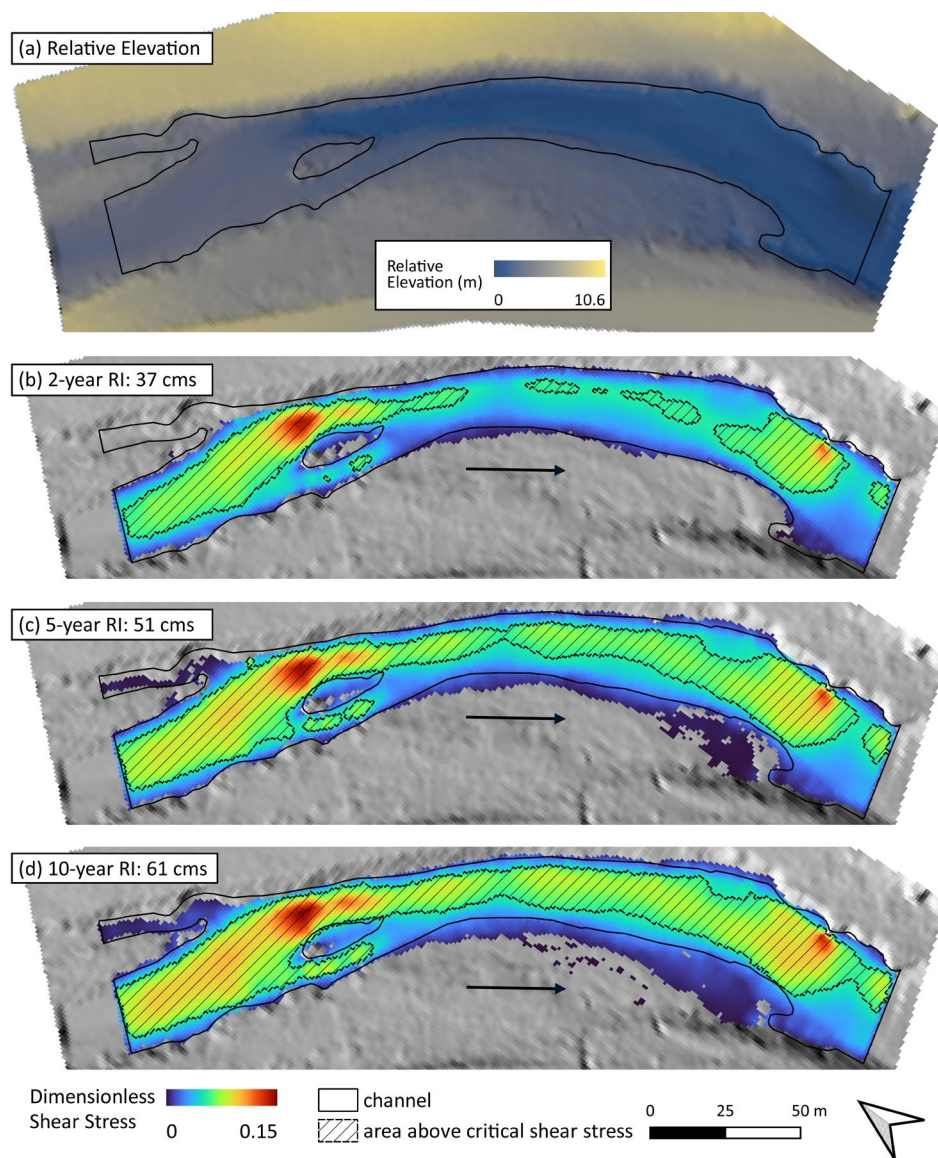


FIGURE 5 | Bed mobilization potential at reach C5. (a) Relative elevation map. Dimensionless shear stress outputs at 2-year (b), 5-year (c), and 10-year (d) return interval flows. Patterned areas indicate where bed shear stress exceeds critical shear stress, indicating bed mobilization. Black arrow indicates flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ra.7064)]

significantly greater ($p=0.005$) fine sediment volumes than canyon reaches downstream from Black Hollow (Figure 2B). Reaches upstream from Black Hollow did not have significantly different volumes of fine sediment relative to downstream canyon reaches or transition zone reaches ($p=0.53$ and $p=0.18$, respectively). Table S3A lists the top 10 models for predicting sediment volume from *dredge* output.

Gradient was inversely correlated with embeddedness ($p=0.005$, $R^2=0.40$), and cross-sectional area showed moderate explanatory power ($p=0.067$, $R^2=0.23$) and a direct correlation with embeddedness. Similar to fine sediment volume, embeddedness values decreased downstream in the canyon and then increased at the transition zone sites (Figure 3A). Pairwise comparisons of estimated means indicated that transition zone reaches had significantly higher ($p=0.003$) embeddedness than canyon reaches downstream from Black Hollow (Figure 3B). The lack

of significant difference between the upstream canyon reaches and the transition-zone reaches may reflect a distortion associated with the small sample size of upstream canyon reaches and the presence of substantial fine sediment at C1, which had the lowest bed gradient of any canyon reach (Table 1). Tables S3B and S3C list the top 10 models for predicting embeddedness and embeddedness by transect, respectively, from *dredge* output.

Embeddedness varied significantly among all channel units (ANOVA, $p < 0.001$) except for the pairs of pools and backwaters ($p=0.09$), side channels and backwaters ($p=0.24$), and pools and side channels ($p=0.97$). Riffles had the lowest embeddedness, followed by runs and then pools. Side channels had a range of values, and backwaters were all 100% embedded. Marginal and conditional R^2 values are 0.32 and 0.46, respectively, and the random effect (reach) accounts for 21% of the total variance (reach variance: 69.41, residual variance: 331.23).

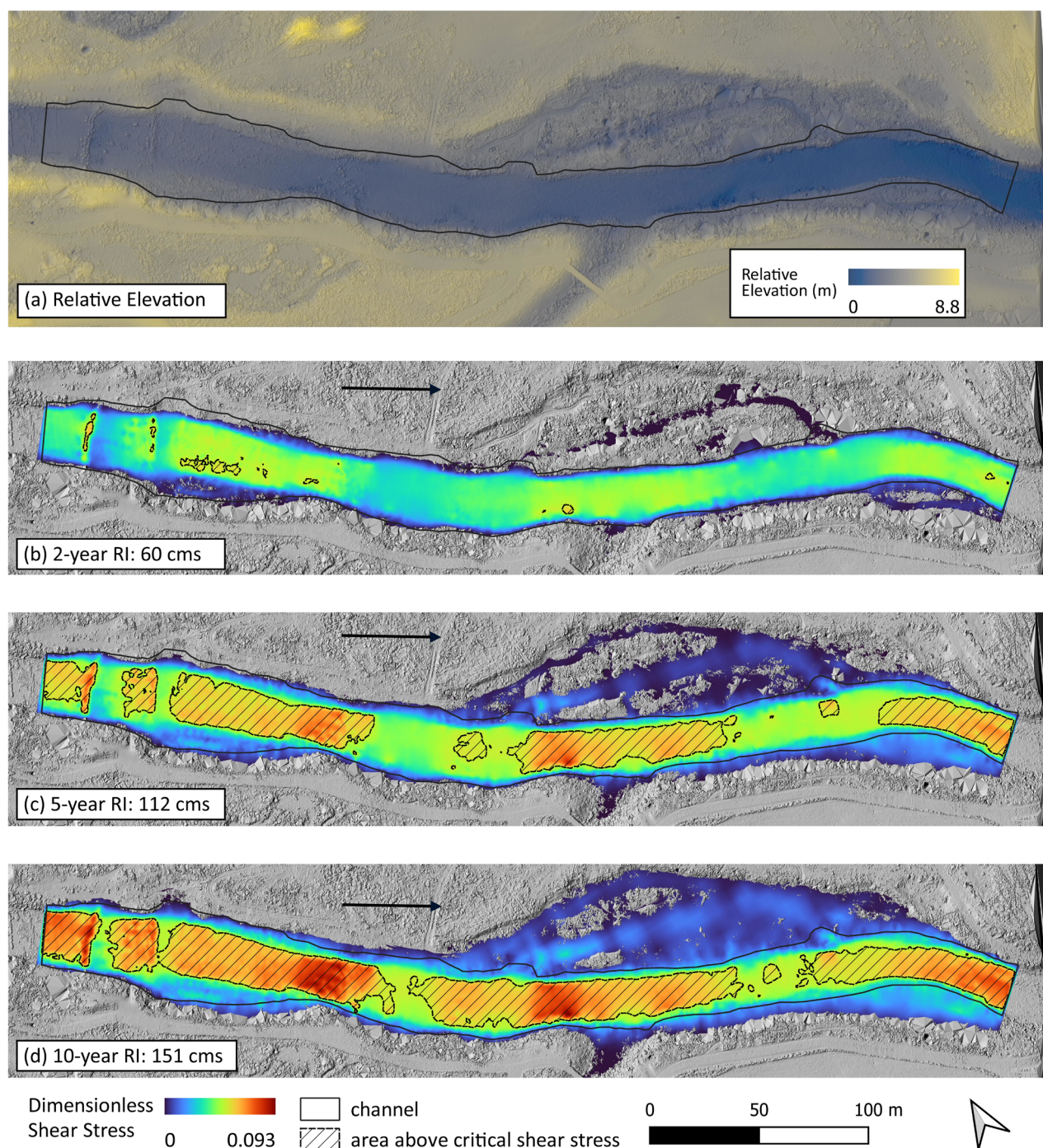


FIGURE 6 | Bed mobilization potential at reach T2. (a) Relative elevation map. Dimensionless shear stress outputs at 2-year (b), 5-year (c), and 10-year (d) return interval flows. Patterned areas indicate where bed shear stress exceeds critical shear stress, indicating bed mobilization. Black arrow indicates flow direction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

4.2 | Estimation of Fine Sediment Remobilization

We estimated the proportion of the channel above the threshold critical shear stress at the 2-, 5-, and 10-year return interval flow for each study reach (Figure 4) and displayed the spatial distribution of estimated dimensionless shear stress at two of the study reaches (Figures 5 and 6). Modeling suggested abundant bed mobilization at the 2-year return flow at the high-gradient canyon site C2, whereas the transition zone sites required the 5- or 10-year return flow to mobilize the bed.

Since the 2020 wildfire, the two canyon reaches have experienced 14 days with flows at or above the 2-year return interval flow, compared to 6.8 and 3.7 days, respectively, for the two transition-zone reaches (Table S4). The two canyon reaches have experienced 1 day at the 5-year return interval flow, and one of the canyon reaches experienced 0.2 days at the 10-year return interval flow during the Black Hollow debris flow and resulting flood on the mainstem Poudre River. Neither transition-zone reach has experienced a 5- or 10-year return interval flow since the Black Hollow debris flow, likely because of flow diversions



FIGURE 7 | Fine sediment deposition in backwaters in the transition zone. (A) and (B) backwaters at reach T8. (C) partially filled backwater at reach T5. (D) filled backwater at reach T4. Arrows indicate the flow direction of the main channel. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

in the transition zone. In summary, bed mobilization likely occurs at different rates throughout the study area and supports the finding that reach location (canyon versus transition zone) correlates with fine sediment retention.

The exposed sand deposits at all sites have a critical shear stress value in the range of 0.03 Pa and a 2-year return interval, and larger flows greatly exceeded this shear stress at all sites (Table S4). The mobilization of exposed sand deposits is thus likely a function of the frequency and duration of moderate annual flow peaks, as well as the continuing supply of sand from upstream post-fire sand deposits.

5 | Discussion and Conclusions

As noted earlier, we regard our estimates of bed-sediment mobilization as approximations. The use of a single D_{50} value and constant critical Shields stress for each site represents simplifications of a more spatially complex reality. We are primarily interested in differences in the mobilization potential for interstitial sand between canyon and transition-zone sites. Exposed sand deposits in the main channel in both canyon and transition-zone sites are readily mobilized by flows that occur every 1–2 years. The sand deposits in areas of flow separation and in the interstices of coarse sediment on the bed, which may be the most critical in terms of limiting fish habitat, require larger flows for mobilization. If environmental flows were designed to mobilize marginal and interstitial sand, it would be necessary to use more spatially distributed grain-size values and modeled values of

critical shear stress to more accurately estimate threshold flows for mobilization at each site.

Although the bank length ratio for study reaches did not correlate significantly with fine sediment volume, the largest fine sediment volumes occurred in backwaters and marginal eddies associated with greater bank lengths. Statistical models may not highlight this observation because these features are small relative to the total length of each reach. However, the habitat alteration via sedimentation in marginal eddies, side channels, and backwaters is likely to be disproportionately important to fishes because these areas (i) are likely to remain below critical shear stress values even during high flows, which limits or prevents fine sediment remobilization, (ii) provide critical nursery habitat for riverine fish communities (Junk et al. 1989; Slipke et al. 2005), and (iii) provide clear, shallow standing water habitat for rare native species including northern redbelly dace (*Chrosomus eos*), plains topminnow (*Fundulus sciadicus*), and Iowa darter (*Etheostoma exile*) (Bestgen 1989; Schumann et al. 2015). This habitat was reduced in size and connectivity to the main channel by fine sediment deposition (Figures 7 and 8).

Native fishes in the Poudre River, including white sucker (*Catostomus commersonii*), longnose sucker (*C. catostomus*), creek chub (*Semotilus atromaculatus*), and longnose dace (*Rhinichthys cataractae*), use gravel substrates for spawning (Haworth and Bestgen 2024). Introduced brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) also use spawning gravels (Becker 1983). The high levels of

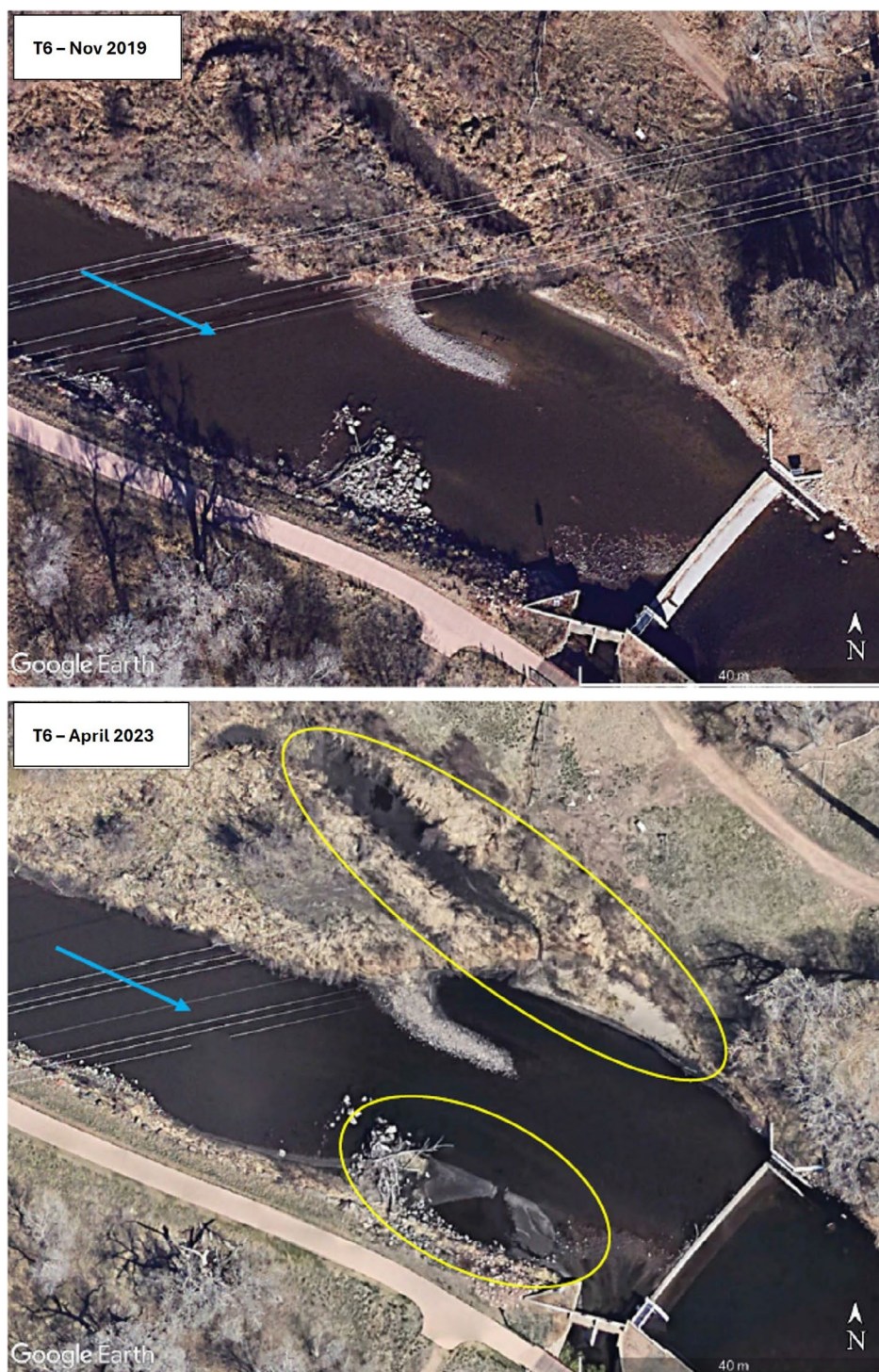


FIGURE 8 | Aerial images from 2019 and 2023 of site T6. Blue arrow indicates flow direction. Yellow circles indicate areas of fine sediment deposition and reduction in backwater connectivity. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ra.7064)]

embeddedness observed at most of the transition zone reaches (Table 1) may preclude the continued presence of these species. Increased abundance of fine sediment and embeddedness can also reduce benthic macroinvertebrate abundance and diversity (Duan et al. 2008; Kemp et al. 2011).

The effects of fine sediment deposition in the transition zone reaches along the Poudre River were exacerbated by channel modifications (bank stabilization, levees, channelization) that reduce the bank length ratio and hydrologically disconnect the

active channel and floodplain, and by flow reductions via diversions from the main channel. Reduced geomorphic complexity and lack of lateral channel mobility in the transition zone limit the river's ability to respond dynamically to increased supplies of fine sediment following wildfire (Shanahan et al. 2014). Fine sediment deposition occurred primarily in the main channel and in the few marginal areas (side channels, backwaters) that remain in transition zone reaches. The persistence of these deposits suggests that the river's artificial lateral stability limits the remobilization and transport of these deposits that would

otherwise occur during high flows. Establishment of vegetation on persistent fine sediment deposits will likely further stabilize these sediments.

The lack of bed mobility at transition zone sites reflects the altered flow regime in this region. Andrews (1984) concluded that coarse-grained rivers draining the Rocky Mountains experience bed mobilization on average during the bankfull flow, which also corresponds to the 2-year return flow. Bed mobilization modeling at site C2, which has a relatively intact flow regime, agrees with Andrews' (1984) findings, but modeling at the transition zone sites suggests that increasingly rare, higher-magnitude flows are needed to mobilize the bed and flush embedded fines. These flows occur less frequently in the transition zone sites because of flow regulation and diversion and increasing drainage area and associated peak flow attenuation, which only exacerbates the discrepancy between canyon and transition zone sites with respect to the likelihood of flushing accumulated fine sediment (Table S3). The frequency of flushing flows in the transition zone is likely to further decrease with the construction of the proposed Northern Integrated Supply Project, which will divert peak flows to fill off-channel reservoirs for municipal and agricultural use (U.S. Army Corps of Engineers 2018).

Wildfires and post-fire debris flows and floods will continue to occur in the Poudre River catchment and fire-prone drylands throughout the world. The results summarized here illustrate how fires in mountainous headwater regions can create persistent fine sediment deposits in the lowland portion of river networks draining mountains. These fine sediment deposits adversely affect native fish populations that may already be stressed by loss of habitat and connectivity, altered flow regimes, and invasive species (Fischer and Paukert 2008; Pasbrig et al. 2012; Schumann et al. 2015). Management designed to mitigate these stressors to fishes can include (i) removing artificial limits to channel mobility, such as artificial levees and armored banks, which would facilitate greater geomorphic complexity and bank length ratios; (ii) modifying river corridor geometry to create multiple inset floodplain surfaces, which would facilitate overbank flows at lower discharges and promote fine sediment deposition outside of the active channel; (iii) creating flow separation zones by designing active channel reaches with islands, side channels, bars, and log-jams; and (iv) mechanically removing accumulated fine sediment to restore lost habitat and connectivity. Choices among these alternatives, which are not mutually exclusive, will partly depend on the lateral constraints in the form of property ownership and infrastructure present at each site along a river.

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Data Availability Statement

All basic data for this research can be found in A.C. Katz, 2024, Shifting Sands: Drivers and Mobilization of Fine Sediment on the

Cache la Poudre River Following a Wildfire. MS thesis, Colorado State University, Fort Collins, CO. <https://mountainscholar.org/items/90da437e-e3f4-4a3f-80a2-cb4a96b77356>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Response & predictor variables used in multiple linear regression analyses. **Table S2:** Objectives & statistical tests used in multiple linear regressions. **Table S3A:** Top 10 models predicting $\log_{10}(\text{volume})$ from *dredge* output for full dataset. Models with delta AICc < 2 were considered to have substantial support and are in bold font. **Table S3B:** Top 10 models predicting embeddedness from *dredge* output for full dataset. Models with delta AICc < 2 were considered to have substantial support and are in bold font. **Table S3C:** Top eight models predicting embeddedness by transect from *dredge* output for main channel transects (not including side channels or backwaters). Models with delta AICc < 2 were considered to have substantial support and are in bold font. **Table S4:** Hydraulic modeling site summaries. **Figure S1:** Hydrograph at five Poudre River stream gauges and distance downstream from the Black Hollow confluence. Flood pulse caused by the Black Hollow debris flow is shown in red. Gauges are operated by the U.S. Geological Survey (Rustic 06747500, Hewlett Gulch 404129105183700, Fort Collins 06752260, Timnath 06752300) and the Colorado Department of Natural Resources (Canyon mouth CLAFTCCO).

Supplemental Material

Supplemental Table 1. Response & predictor variables used in multiple linear regression analyses

Variable	Units
<i>Response</i>	
Volume of fines per bankfull volume	m ³ /m ³
Embeddedness	%
<i>Predictor – distance downstream</i>	
Distance downstream from Black Hollow	km
Reach location	NA
<i>Predictor – reach-specific</i>	
Bed gradient	m/m
Width/depth ratio	m/m
Cross-sectional area	m ²
Bank length ratio	m/m
<i>Predictor – transect</i>	
Bedform	NA

Supplemental Table 2. Objectives & statistical tests used in multiple linear regressions

Objective & statistical tests	Formula	Notes
<i>Volume by reach</i> lm, ANOVA, pairwise comparisons Model selection - dredge	Volume ~ reach location Volume ~ reach location + gradient + XSA + WDR + BLR	n = 18; skew right; log ₁₀ transformation
<i>Embeddedness by reach</i> lm, ANOVA, pairwise comparisons Model selection - dredge	Embed ~ reach location Embed ~ reach location + gradient + XSA + WDR + BLR	n = 18; skew right; log ₁₀ transformation
<i>Embeddedness by transect</i> lmer, ANOVA, pairwise comparisons Model selection - dredge	Embed ~ bedform + (1 site) Embed ~ reach location + bedform + XSA + WDR	n = 213; normal distribution n = 185; main channel only; normal distribution

XSA is cross-sectional area

WDR is width/depth ratio

BLR is bank length ratio

Supplemental Table 3A. Top ten models predicting $\log_{10}(\text{volume})$ from *dredge* output for full dataset. Models with delta AICc ≤ 2 were considered to have substantial support and are in bold font.

Model	df	AICc	Delta AICc	AICc weight	Log likelihood
location	4	25.78	0.00	0.30	-7.35
grad_bed	3	26.94	1.16	0.17	-9.61
BLR + location	5	27.88	2.10	0.10	-6.44
location + grad_bed	5	28.66	2.88	0.07	-6.83
BLR + grad_bed	4	28.86	3.08	0.06	-8.89
Location + WDR_avg	5	28.95	3.17	0.06	-6.97
Location + XSA_avg	5	29.57	3.79	0.04	-7.29
grad_bed + WDR_avg	4	30.13	4.36	0.03	-9.53
grad_bed + XSA_avg	4	30.29	4.51	0.03	-9.61
BLR + location + grad_bed	6	31.55	5.77	0.02	-5.96

location is reach location

grad_bed is bed gradient

BLR is bank length ratio

WDR_avg is average width-to-depth ratio

XSA_avg is average cross-sectional area

Supplemental Table 3B. Top ten models predicting embeddedness from *dredge* output for full dataset. Models with delta AICc ≤ 2 were considered to have substantial support and are in bold font.

Model	df	AICc	Delta AICc	AICc weight	Log likelihood
location	4	-34.71	0.00	0.30	22.89
grad_bed	3	-33.00	1.71	0.13	20.36
location + XSA_avg	5	-32.85	1.86	0.12	23.93
grad_bed + location	5	-32.48	2.23	0.10	23.74
location + WDR_avg	5	-31.29	3.42	0.05	23.14
BLR + location	5	-30.80	3.90	0.04	22.90
grad_bed + XSA_avg	4	-30.60	4.11	0.04	20.84
grad_bed + WDR_avg	4	-30.47	4.23	0.04	20.77
BLR + grad_bed	4	-29.64	5.07	0.02	20.36
location + WDR_avg + XSA_avg	6	-29.60	5.11	0.02	24.62

location is reach location

grad_bed is bed gradient

BLR is bank length ratio

WDR_avg is average width-to-depth ratio

XSA_avg is average cross-sectional area

Supplemental Table 3C. Top eight models predicting embeddedness by transect from *dredge* output for main channel transects (not including side channels or backwaters). Models with delta AICc ≤ 2 were considered to have substantial support and are in bold font.

Model	df	AICc	Delta AICc	AICc weight	Log likelihood
bedform	5	1503.4	0.00	0.46	-746.71
bedform + XSA	6	1504.5	1.1	0.27	-746.25
bedform + WDR	6	1505.4	1.9	0.17	-746.68
bedform + WDR + XSA	7	1506.5	3.1	0.10	-746.24
WDR	4	1583.5	80.1	0.00	-787.77
WDR + XSA	5	1583.7	80.3	0.00	-786.84
intercept model	3	1584.1	80.7	0.00	-789.05
XSA	4	1585.0	81.6	0.00	-788.51

WDR is width-to-depth ratio

XSA is cross-sectional area

Supplemental Table 4. Hydraulic modeling site summaries

Reach	S (m/m)	D ₅₀ (mm)	Embed (%)	RI (y)	Q (m ³ /s)	# days	τ_c^* (-)	τ_c (Pa)	Proportion of channel $\geq \tau_c$ (%)
C2	0.005	43	56	2	37	14	0.052	36	0
				5	51	1			1
				10	61	0			4
C5	0.009	107	54	2	37	14	0.054	96	31
				5	51	1			50
				10	61	0.2			59
TZ2	0.006	65	61	2	60	6.8	0.05	56	1
				5	112	0			36
				10	151	0			54
TZ8	0.001	43	72	2	54	3.7	0.052	36	3
				5	105	0			13
				10	143	0			20

S is bed gradient; Embed is embeddedness; RI is return interval; # days is number of days that discharge in preceding column was equaled or exceeded between 2020 wildfire and end of 2023 runoff season; τ_c^* is critical shear stress and τ_c is modeled shear stress

Supplemental Figure 1. Hydrograph at five Poudre River stream gauges and distance downstream from the Black Hollow confluence. Flood pulse caused by the Black Hollow debris flow is shown in red. Gauges are operated by the U.S. Geological Survey (Rustic 06747500, Hewlett Gulch 404129105183700, Fort Collins 06752260, Timnath 06752300) and the Colorado Department of Natural Resources (Canyon mouth CLAFTCCO)

