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Comparing the Sources of Sediment Retained by Beaver Dams and Beaver Dam Analogs

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Key Points:

- Sediment fingerprinting can effectively establish the source of sediment retained by beaver dams and beaver dam analogs (BDAs)
- Sediment retained by beaver dams originates from different and more diverse sources than sediment retained by BDAs
- BDA sediment composition does not replicate that of beaver dams as beavers contribute sediment via canal building and terrace inundation

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Abstract

Beavers modify riverine systems by building dams that alter downstream fluxes of water and sediment. Where beavers have been lost and stream channels degraded, beaver dam analogs (BDAs) are being used to mimic the effects of beaver engineering. Central to the success of these structures in accelerating stream recovery is creating similar ecosystem responses as beaver dams including sediment retention. Unknown is the relative importance of beaver actions versus erosion in the catchment in generating the retained sediment. This study tested the viability of sediment fingerprinting to determine the source of sediment retained by beaver dams and BDAs in a watershed in Alberta, Canada. Concentrations of 29 elements were measured as potential tracers from known sediment sources: upland, terrace, stream bank, and beaver canal. Virtual mixture tests, used to compare the computed source estimates with known source mixtures, revealed that sediment fingerprinting is a robust method for identifying sources of sediment retained by beaver ponds and BDAs. The un-mixing model results indicate that on average 56% of the sediment retained by the beaver dams originated from terraces, 23% from uplands, and 13% from beaver canals. About 89% of sediment retained by the BDAs originated from eroding stream banks. We conclude that the geomorphic effects of beavers and their dams are more diverse, resulting in more diverse sources of sediment retained by their dams. This differentiates beaver dams from BDAs. The study has implications for informing management practices that involve beavers and beaver mimicry.

Plain Language Summary

Growing recognition of the importance of beaver dams in maintaining naturally functioning streams and floodplains has spurred the use of beaver mimicry structures to accelerate stream recovery where stream channels have cut downward because beavers are absent. Despite the importance of sediment trapping in determining the success of beaver mimicry structures in raising the stream bed, the source of the trapped sediment is poorly known and seldom analyzed. This study investigated whether sediment fingerprinting, a well-known method for assessing sources of lake, estuary and floodplain sediment deposits, could reliably establish the sources of sediment retained by beaver dams and beaver mimicry structures. We tested this method in a watershed in the Canadian Rocky Mountains and found that it effectively differentiated between the sources of sediment trapped by beaver dams and beaver mimicry structures. Sediment trapped by the mimicry structures originated mainly from stream banks flooded by the structures, whereas beaver dams trapped sediment originating from a combination of riparian areas, canals dug by beavers and hillslopes. Beaver mimicry structures did not replicate the sediment trapping processes of beaver dams because the beavers were important in actively mobilizing the sediment that became trapped by their dams.

1. Introduction

Beavers (*Castor canadensis* and *C. fiber*) build dams that profoundly change how water, sediment, nutrients, and energy flow through stream corridors. These processes can enhance habitat diversity and landscape connectivity (Larsen et al., 2021; Wohl, 2021). Humans are captivated by learning from nature and trying to mimic it, especially in degraded environments. There is considerable eagerness to use beaver mimicry structures, often termed beaver dam analogs (BDAs; Pollock et al., 2014) or simulated beaver structures (Bilyeu et al., 2008), as a cost-effective tool to restore eroding and incised streams. BDAs are typically used in places where channels have become degraded and incised to the point where streams are disconnected from their valley bottoms and where beavers are no longer present and cannot survive (Lautz et al., 2019). In some cases, the riparian water table has declined and riparian vegetation has significantly changed and cannot support the building material and/or food needs of beavers (Marshall et al., 2013; Scamardo et al., 2022; Westbrook et al., 2006). The use of BDAs in stream enhancement projects, often without associated post-implementation monitoring, is especially prevalent in the western United States (Nash et al., 2021) and is outpacing the research (Pilliod et al., 2018). Do BDAs create similar ecosystem responses as active beaver dams? Their installation has not consistently led to sediment accumulation in channels or reduced downstream sediment delivery (e.g., Davis et al., 2021; Orr et al., 2020; Pearce et al., 2021). It is unclear if BDAs affect the processes that control the rates of incision and aggradation so that a stream reach may have a net increase in sediment retention from comparable sediment sources to beaver dams.

Beaver dams impede flow and spread water across the dam crest that is usually wider than the original channel (Gurnell, 1998). Backwater pooling caused by dams results in a stair-step channel profile and a decrease in stream power and velocity (Naiman et al., 1988). Lower stream velocity promotes mineral sediment and particulate organic matter deposition in beaver ponds (Burchsted et al., 2010; Butler & Malanson, 1995; Laurel & Wohl, 2019; McCreesh et al., 2019; Naiman et al., 1986; Pollock et al., 2007). Sedimentation rates are partially regulated by local trapping efficiency, for example, dam impermeability to water throughflow. They are also regulated by the sediment supply rate as this rather than transport capacity limits sediment yields from headwaters where beavers build dams (Church, 2002; Gurnell, 1998; Larsen et al., 2021). The thickest area of sediment deposition in beaver ponds is typically the wedge against the upstream face of the dam (Larsen et al., 2021). Sediment is deposited elsewhere in the pond in either a coherent or incoherent pattern (Bigler et al., 2001). Older beaver ponds tend to hold more sediment and have higher sedimentation rates while larger ponds tend to store greater volumes of sediment (Meentemeyer & Butler, 1999; Wohl & Scott, 2017). Further, sediment trapping is greatest at low and medium stream discharge (Larsen et al., 2021; Persico & Meyer, 2009). Beaver pond formation also leads to redirection of streamflow toward banks (Janzen & Westbrook, 2011), which can saturate them and reduce their resistance to erosion (Bull, 1997). Beaver dams also create significant overbank flow and sedimentation on floodplains, the area inundated by a river during high water events in its *current* hydrological regime, and on terraces, areas adjacent to a river that are inundated during high water events in its *past* hydrologic regimes (Westbrook et al., 2006). As the formation of terraces typically requires incision, either after deposition for the creation of a fill terrace, or incision resulting in a strath terrace if the terrace is composed of bedrock with a thin veneer of alluvium, terraces occur at higher elevations of valley bottoms (Merritts et al., 1994). Sediments that accumulate on floodplains and terraces due to beaver dam triggered overbank flows tend to have a longer residence time than sediments that accumulate in the channel (Kramer et al., 2012; Levine & Meyer, 2014), and can result in the formation of beaver meadows and the rejuvenation of riparian vegetation (Polvi & Wohl, 2012; Westbrook et al., 2011). Beaver dams often change the depositional sediment regime enough to alter channel sediment budgets (Brazier et al., 2021).

While sediment supply is affected by factors such as geology (Bywater-Reyes et al., 2017), climate (Langbein & Schumm, 1958) or catchment disturbance history (Owens et al., 2010), for streams with beavers, other factors affecting sediment supply must also be considered. Beavers are agents of erosion in addition to being dam builders (Westbrook et al., 2017). Beavers mobilize sediment by excavating canals on the bottom of ponds, termed benthic canals, and along their flanks to connect aquatic habitat across floodplains (Grudzinski et al., 2020). Little is known about the fate of sediments excavated during canal building. There have been conflicting reports of sediments being piled on the banks of canals (Grudzinski et al., 2020) and canals without adjacent sediments (Larsen et al., 2021). Regardless, canal construction is expected to increase sediment flux to streams (Brazier et al., 2021; Butler & Malanson, 1995; Hood & Larson, 2015). Beaver also burrow into channel banks contributing directly to stream sediment load (de Visscher et al., 2014; Lamsodis & Ulevičius, 2012; Meentemeyer et al., 1998) and indirectly to stream sediment load as it weakens bank structure and increases their potential to collapse (Larsen et al., 2021).

Beavers are known geomorphic agents (Meentemeyer et al., 1998), but previous research has been vague about the source(s) of sediments deposited in beaver ponds (Brazier et al., 2021; Larsen et al., 2021). An exception is Puttock et al. (2018) who studied sediment trapping efficiency and concluded that >70% of the sediment trapped by beaver dams originated from catchment erosion because the estimated pond sediment storage rates were comparable to local known rates of catchment erosion for the same land use. Without a clear understanding of the major sources of suspended sediment retained by beaver dams, it is difficult to understand if and under what environmental and geomorphic settings BDAs have comparable effective sediment retention to beaver dams (Davis et al., 2021; Pearce et al., 2021; Scamardo & Wohl, 2020), and therefore if BDAs create similar geomorphic responses to beaver dams. It is also more difficult to determine the appropriate placement of BDAs to promote channel aggradation. It is important to address the persistent question first raised by Butler and

Malanson (1995): are beavers generating a significant proportion of the sediment that accumulates behind their dams via their normal actions or does most of the sediment retained by beaver dams result from passive capture of sediment supplied by catchment erosion?

There has long been interest in advancing approaches to identify which landforms (e.g., upland soils) or processes (e.g., landslides) contribute sediment that either passes by a particular stream location, such as a gauging station, or that collects in watershed storage zones such as lakebeds, reservoirs or estuaries. This interest is driven by environmental concerns over soil erosion and the degradation of waterways by excess sediment loading (Batista et al., 2022; Wall & Wilding, 1976). Technological advances in measuring patterns of watershed erosion or estimating them with modeling have occurred (Walling, 2013). However, it is difficult to use erosivity to estimate the provenance of suspended sediment loads owing to variable source-river connectivity and uncertainties associated with accurately tracking sediment movement through a watershed (Collins & Walling, 2004; Janes et al., 2018). Therefore, sediment fingerprinting may be the best direct approach for differentiating primary sources of suspended sediment in stream systems because it only deals with the biogeochemical and physical properties of sediment, circumventing the problem of accurately defining sediment delivery (Xu et al., 2022).

Sediment fingerprinting involves selecting a set of sediment properties to use as tracers (i.e., the fingerprint) that can distinguish between potential sediment sources. The tracers are measured in both the potential source areas and the deposited (target) sediment areas, and an un-mixing model is used to apportion the time-integrated contribution of each potential source to the target. The most commonly used tracers are elemental signatures, although the use of compound-specific stable isotopes, sediment color, and eDNA is increasing (Collins et al., 2020). Given that beaver ponds are a sediment storage feature in stream systems, sediment fingerprinting could be a useful technique for investigating watershed sources of sediment retained by them.

For fingerprinting to be a viable beaver pond sediment identification technique there must be consideration of not only upland sediment, but also streambank, floodplain and terrace soils mobilized by sediment excavation activities of beavers. Few previous sediment fingerprint studies have included floodplains, banks and terraces as distinct sediment sources even though the hydrological connection of valley bottoms to channels is well known and documented (Belmont et al., 2014), particularly in beaver-dominated systems (Westbrook et al., 2006). The challenge is that although banks, floodplains and terraces are all functionally stream storage zones, it can be difficult to find conservative floodplain and bank tracers with values distinct from their terrestrial source areas (Belmont et al., 2014). Bank and floodplain sediments also can have overlapping ranges of individual tracers owing to their close proximity and depositional histories (Williamson et al., 2023). Terrace sediments tend to be overlooked in unraveling contemporary sediment dynamics of rivers as it is thought that they are primarily remobilized by a river's past, not current, hydrological regime and so are usually only incorporated into investigations of historical sediment dynamics of rivers (D’Haen et al., 2012; Belmont et al., 2014).

In this study we explored the potential of sediment fingerprinting to distinguish sediment source contributions to beaver dams and the most commonly used type of beaver mimicry structure, BDAs. We first determined if this simple method could reliably establish the provenance of sediment retained by beaver dams and BDAs. Second, a goal of BDA use is to increase stream bed elevation and facilitate stream recovery from incision (Pollock et al., 2014; Wohl, 2021). However, it is unclear whether these structures create similar ecosystem responses as beaver dams due to a broad range of beaver-sediment interactions. Therefore, we evaluated how the origin of sediment retained by BDAs compares to beaver dams. We hypothesized that sediments retained by beaver dams would originate from a combination of local sources, owing to the actions of beavers, as well as upstream catchment erosion whereas sediments retained by BDAs would originate primarily from upstream catchment erosion. This novel application of sediment fingerprinting to determine the provenance of sediment retained in ponds created by natural and human-made structures provides a tool that could provide new insights into beaver-based stream and riparian recovery.

2. Methods

2.1. Site Description

The study was carried out in the headwaters of Pine Creek (Figure 1) within the Ann and Sandy Cross Conservation Area, between the city of Calgary and the town of Priddis, Alberta, Canada (50.8776°N, 114.2331°W; watershed area 202 km^2). It is in the Foothills Parkland ecoregion with native aspen parkland vegetation.

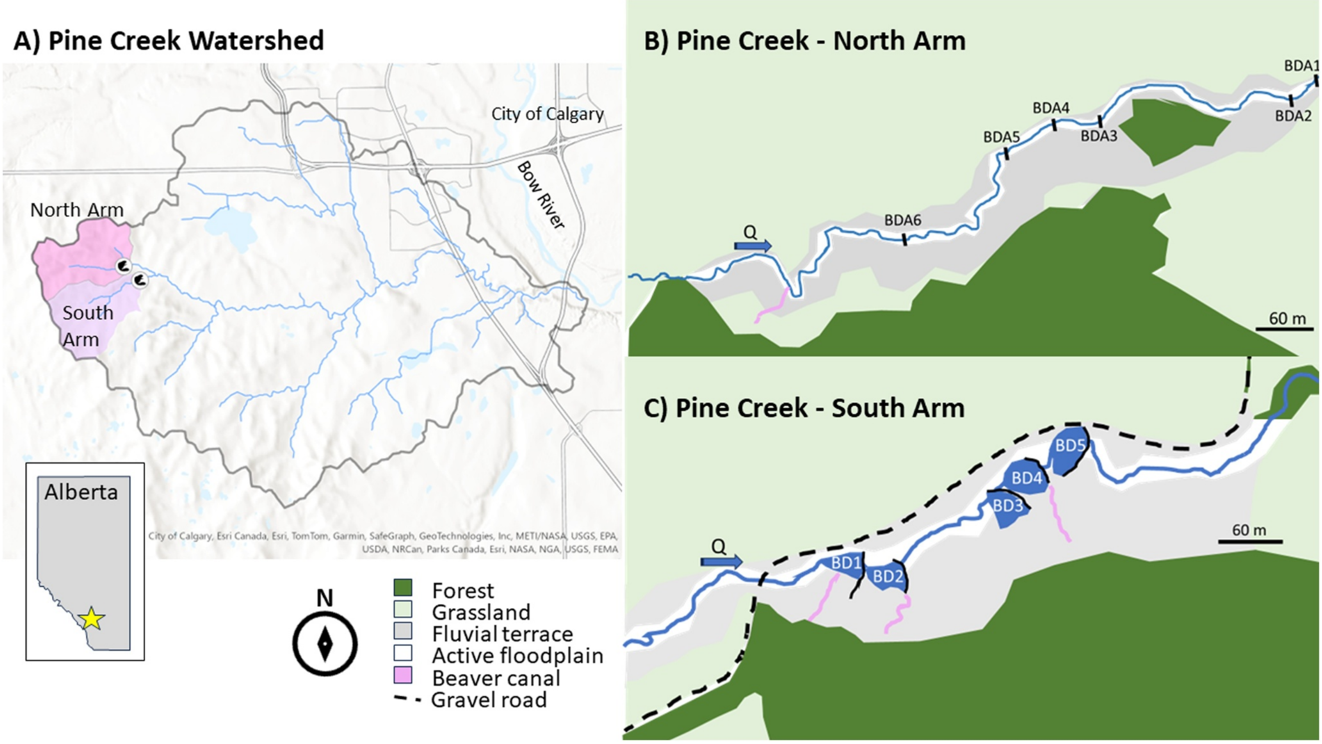

Figure 1. Map of the study site. (a) Location of Pine Creek watershed (yellow star) in Alberta (inset) and location of the north arm and south arm study areas of Pine Creek (map scale 1:30,000). Locations of study areas are demarcated by beaver icons. Site maps of the north (b) and south (c) arms of Pine Creek showing location of beaver dams (BD#) at the time of sediment sampling and beaver dam analogs (BDA#). Q is streamflow and the arrow indicates flow direction.

Dominant species include trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*) and Lodgepole pine (*Pinus contorta*) forest interspersed with rough fescue (*Festuca scabrella*) grassland that is used to pasture cattle. Plant species nomenclature follows Hallworth and Chinnappa (1997). The underlying bedrock of the watershed includes the Paskapoo formation composed of calcareous sandstones and mudstones with minor shale and coal beds (Carrigy, 1970). There are many groundwater-fed springs in the area, some of which have small water detention structures for cattle watering. Pine Creek flows eastward to the Bow River. It has an average width of 0.6 m (Munir & Westbrook, 2021a), a slope of ~0.01 m/m and a snowmelt-dominated streamflow regime. The watershed is within the thin black soil zone of southwestern Alberta and soils are classified as highly productive Chernozems with some Luvisols and Gleysols (Reid & Heseltine, 1997). Local soil erodibility is annually ~600 g/m^2 in forested areas and ~225 g/m^2 in grassland areas (Luk, 1978).

In the study area, Pine Creek has two arms: north and south arm (Figure 1). These arms are ~800 m apart, separated by a hill that peaks at 1,202 m elevation, and have drainage areas of 8.13 and 8.02 km^2. Beavers were removed from the Pine Creek headwaters in the early 1990s by illegal trapping (G. Shyba, pers. comm.). Beavers are unable to naturally re-disperse into the portion of the creek because it is fenced to its bed at the boundary of the conservation area to ensure the security of bison which are ranched on the adjacent, downstream land. Remnant, valley-spanning beaver dams with large gaps at the stream channel and a relict >60 m long beaver canal are still clearly visible in the north arm of Pine Creek but in the absence of beavers, the creek and riparian area (elevation 1,140 m) have degraded. The stream channel is incised (bank height ~0.60 m) and the riparian *Salix* spp. Shrubs are either dead or severely degraded, meaning living willows had <20% live stems. Beavers were re-introduced to the south arm of Pine Creek in 2015 and during the study period a series of five beaver dams occurred along a 425-m reach (elevation 1,131 m; bank height ~0.40 m). As viewed on Google Earth, the first beaver pond was built in 2015 (dam length 46 m) at the most downstream position along the reach. Two additional ponds were built in 2016, located mid reach (dam length 19 m) and in the most upstream position of the reach (dam length 21 m), and two ponds were built in 2017 in the middle of the reach (dam lengths 15 and 24 m). All five beaver dams had heights of about 1 m, but exact values were not recorded. The riparian area of the reach of the south arm had sparse but living *Salix* spp. Shrubs in 2017 and 2018. There were three beaver canals in the south arm at the time of sampling (Figure 1). These were excavated through the stream banks and terrace, and terminated at the valley margin. The mean terrace elevation was approximately 0.7 m higher than the mean bank height.

Conservation area land managers are interested in re-introducing beavers to the north arm of Pine Creek, however, the channel and riparian vegetation are too degraded to support beavers and stream and riparian vegetation restoration are necessary. We carried out a 1-year field experiment starting in spring 2018 that included the installation of six BDAs along a 1,072 m reach (Munir & Westbrook, 2021a) with a gradient of 0.013 m/m and a mean terrace elevation approximately 0.8 m higher than the mean bank height. The BDA design used was typical of those constructed throughout North America (Pollock et al., 2012). They were constructed in early August 2018 using wooden posts (1.0 m long, 0.07 m in diameter) that were hand driven into the stream bed in a line spanning the channel width. Aspen branches harvested on-site were interwoven through the line of posts to pool water upstream to an initial depth of 0.60 m. The BDAs were damaged by ice in winter 2018–2019 and repaired in April 2019 following stream ice-off. Whether or not damage was incurred in summer of 2019, the BDAs were not again repaired. Hydrological observations related to the experiment ceased in September 2019 (Munir and Westbrook, 2021a, 2021b).

2.2. Soil and Sediment Sampling Design

Stratified sediment sampling was conducted in the north and south arms of the headwaters of Pine Creek. Potential surface sediment sources in the headwaters of the Pine Creek watershed included upland areas (forested and grassland), and the fluvial terrace, and subsurface sediment sources of stream banks and beaver canals. Samples from the active floodplain were not collected as Belmont et al. (2014) indicated it can be difficult to find conservative tracers that distinguish floodplain from bank sediments. Soil samples were collected on two different occasions, August 2018 and May 2019, from the five potential sources in the watershed. Source sediment sampling sites were not marked with Global Positioning System coordinates. Each sample from surface sources ($n = 10$ for grassland, $n = 10$ for forest, $n = 12$ for terrace) consisted of 5–10 subsamples taken with a plastic trowel from the top 5 cm of the soil profile, as this would be most erodible, after brushing away the litter layer. Channel bank samples ($n = 10$) were composites of 5–10 subsamples collected by scraping the bank face close to but above the water surface at locations upstream of beaver and BDA ponds. A limited number of beaver canals were observed in the headwaters of Pine Creek (Figure 1). Canal samples ($n = 3$) were composites of 5–7 subsamples scraped from the upper 5 cm of the canal bed along the length of the three canals in the south arm of Pine Creek. The one canal in the north arm of Pine Creek was inadvertently omitted from our sampling. We only became aware of this canal during the preparation of Figure 1, which occurred after we had completed our sediment sampling. Target (mixed) sediment samples were collected from all of the beaver ponds that existed at the time of study ($n = 5$) on the south arm of Pine Creek and all of the BDA ponds ($n = 6$) on the north arm of Pine Creek in May 2019. The thickest area of sediment deposition in beaver ponds is typically the sediment wedge against the upstream face of the dam. Beaver ponds had roughly 5–10 cm of retained sediment whereas BDAs had roughly 5 cm of retained sediment. Therefore, beaver pond and BDA sediment was sampled as composites of 5–10 subsamples from the uppermost ~2 cm of the sediment wedge to ensure we were collecting sediment retained by the structures rather than bed material.

2.3. Laboratory Analysis

Geochemical fingerprints were used to discriminate between potential sediment sources in the Pine Creek watershed. Sediment samples were oven-dried (60 C for 5 days) then dry sieved to <63 μm in the lab to facilitate direct comparison of source and target sediments. This is the most commonly used size fraction because it is generally representative of the majority of sediment sizes transported by streams (Collins et al., 2020). The dried and sieved samples were then ground by hand with mortar and pestle. Elemental geochemistry of the ground samples was determined with a laser ablation inductively coupled plasma mass spectrometer system at a commercial laboratory (SRC Environmental Analytical Laboratories, Saskatoon, Saskatchewan) for 29 elements: silver (Ag), aluminum (Al), antimony (Sb), argon (Ar), boron (B), barium (Ba), beryllium (Be), calcium (Ca), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), nickel (Ni), phosphorus (P), lead (Pb), selenium (Se), tin (Sn), strontium (Sr), titanium (Ti), thallium (Tl), uranium (U), vanadium (V), and zinc (Zn).

2.4. Fingerprint Identification

Selection of the geochemical properties that comprise the composite fingerprint is critical to achieving realistic modeling estimates of the relative contributions of sediment sources to a sink. The composite fingerprint should be developed for each site from a suite of diagnostic properties that are chemically stable. As shown by Sherriff et al. (2015), the non-conservative behavior of a single tracer included in a mass balance mixing model can affect the predicted source sediment contributions. Therefore, Koiter, Lobb, et al. (2013) recommend that statistical and process knowledge-based methods should be used to identify the optimal fingerprint in a watershed.

The three-step method is a statistical procedure widely used to identify the minimum number of tracers that will produce an "optimum" fingerprint based on levels of source discrimination (Collins & Walling, 2002). We applied the three-step method following Batista et al. (2022). In the first step, a boxplot-based range test (RT) is used, and to pass this test the interquartile range (IQR) of a tracer value must be bracketed by the IQRs of the tracer concentration (mg/kg) in the source groups. In the second step, a Kruskal-Wallis H-test (KW) is used to identify significant differences for the individual fingerprint properties between the medians of the sources (at $p < 0.05$). In the third step, a stepwise discriminant function analysis (DFA) is used to define a minimum set of tracers from those passing the KW test. DFA maximizes the discrimination between sediment sources while minimizing the number of tracers, as identified by minimization of Wilk's lambda (at $p < 0.1$). The statistical procedures were carried out in R using the *FingerPro* package version 1.3 (Lizaga et al., 2020a). Principal components analysis (PCA) was used to visualize the discrimination amongst the sediment sources with the tracers identified by the three-step statistical procedure. We used the *FactoMineR* package to compute the PCA (Lê et al., 2008), the *factoextra* package to extract and visualize the results (Kassambara & Mundt, 2020), and the *cowplot* package to layout the plots (Wilke, 2024). Boxplots were used to visualize concentrations of each element identified by the three-step statistical procedure, built using the *ggplot2* package (Wickham, 2016). Differences in the element concentrations amongst sediment sources were assessed using the KW with Dunn's test, Bonferroni adjusted for multiple comparisons as the Shapiro-Wilk's test indicated the elements had non-normal distributions ($p < 0.05$). We used the *rstatix* package (Kassambara, 2023) to compute these tests.

Applying the three-step method alone can result in retention of erroneous tracers that can lead to the existence of multiple fingerprint model solutions (Lizaga et al., 2020b). Therefore, we followed the three-step method with the consensus and consistent tracer selection method (Latorre et al., 2021), run in R using the *FingerPro* package (Lizaga et al., 2020a), to further remove tracers likely to lead to multiple model solutions. The conservativeness index provides an assessment of the variability of the solutions provided by each individual tracer in a fingerprint by considering multiple virtual mixture scenarios (Latorre et al., 2021; Lizaga et al., 2020b). The conservativeness index has possible outcomes of zero and less; we used a threshold of >-0.3 for the element to be further considered. The consensus ranking metric identifies how substantially each individual tracer influences the output fingerprint model by running single tracer models and determining how often a tracer produces results in conflict with the results produced by clusters of other tracers (Latorre et al., 2021; Lizaga et al., 2020b). The consensus ranking metric has possible outcomes of 0–100; we used a threshold of ≥ 85 for the element to be further considered. An element was required to meet both the conservativeness index and consensus ranking thresholds for inclusion in the composite fingerprint.

2.5. Un-Mixing Model

A standard linear multivariate un-mixing model was used to apportion sediment source contributions for each mixture using the composite fingerprint. The un-mixing model chosen was the *FingerPro* package (Lizaga et al., 2020a) which employs a Monte Carlo random sampling system to identify the relative contribution of different sources to the target sediment and the uncertainties. Model convergence was achieved with 200 iterations. *FingerPro* uses frequentist-as opposed to Bayesian distribution-based principles, but has been shown to produce consistently similar accuracy and uncertainty as MixSIAR which uses a Bayesian approach (Gaspar et al., 2019). Probability distributions were used to visualize the fractional contribution of each sources to the sediment retained by individual BDA and beaver dam, built using *FingerPro*. Boxplots were used to visualize mean sediment source apportionment for BDAs and beaver dams, built using the *ggplot2* package (Wickham, 2016).

2.6. Assessment of Un-Mixing Model Performance

It is becoming commonplace for fingerprinting studies to demonstrate the accuracy of the un-mixing model source contributions by including results generated from a second fingerprint or by using virtual or artificial mixtures (Collins et al., 2020). As we did not have a second, independent tracer data set, we opted to assess model accuracy with virtual mixtures. Virtual mixtures were produced mathematically by multiplying median source tracer values by a varying proportion in each mixture for 30 different scenarios. The various combinations of sources in the virtual sample mixtures aimed to be representative of the range of source apportionment mixtures, with apportionments summing to 100%. The un-mixing model described above was used to apportion sediment source contributions for each virtual mixture scenario separately using the composite fingerprint. Virtual mixture modeling results were visualized on a 1:1 plot built using the *ggplot2* package (Wickham, 2016).

As with any environmental model (Clark et al., 2021), multiple metrics should be used to provide a well-rounded evaluation of un-mixing model accuracy and uncertainty (Batista et al., 2022). We therefore examined four common metrics to evaluate the performance of the un-mixing model in predicting the source composition of virtual mixtures. The selected metrics were run using the *metrica* package (Correndo et al., 2022) and included measures of error (mean bias error (MBE) and averaged root mean squared error (RMSE)), and goodness-of-fit (Nash-Sutcliffe efficiency (NSE) and Kling Gupta efficiency (KGE)). RMSE indicates the magnitude of the average error while MBE describes the direction of the error bias (Willmot, 1982). Values of RMSE and MBE closer to zero are ideal. Negative values of the MBE indicate underestimation and positive values indicate overestimation. The NSE is a normalized variant of mean squared error that compares the performance of the model against the mean of the known data (Nash & Sutcliffe, 1970). Values closer to one are ideal and indicate the model has predictive skills whereas a value of zero indicates all sediment sources should just be considered as equally contributing to the mixture. Negative values indicate poor model performance. The KGE differs from the NSE as it is not derived from the mean squared error; rather, it is the Euclidean distance computed using the coordinates of bias, standard deviation and correlation (Gupta et al., 2009). Similar to the NSE, values of the KGE range from minus infinity to one, where one is ideal.

3. Results

3.1. Source Differentiation

Of the 29 geochemical elements measured for each potential source and target sediment sample, five occurrences were censored data with concentrations below instrument detection limits. Four samples had Ag concentrations below the detection limit of 0.1 mg/kg, and in one sample Sb concentration was below the detection limit of 0.02 mg/kg. A replacement value equal to one-half of the detection limit was assigned to censored data for analysis purposes (Hornung & Reed, 1990). The data set of mean and median element concentrations for source and target sediments and detection limits is archived in a data repository (Westbrook & Cooper, 2024).

During the three-step method, two elements (Co, Mg) were removed from the data set because these did not comply with the RT criteria, as their values in the deposited sediment were not bracketed by the IQRs of the tracer value in the sediment source groups (Table 1). Twelve elements (Al, An, Be, B, Co, Cr, Pb, Ni, P, Ag, Sn, Zn) were removed from the data set because they did not comply with the Kruskal-Wallis test criteria, that is, $p > 0.05$ (Table 1), and 17 elements (Al, Sb, Ar, Ba, Be, B, Cr, Co, Cu, Fe, Pb, Mo, Na, Sr, Tl, Sn, V) were removed from the data set because they did not comply with the DFA test criteria (Table 1). Seven elements met the three-step statistical procedure, Ca, Cd, K, Mn, Se, Ti, and U.

The scatterplot of the first, second and third PCA axes for the seven retained elements explained 75.5% of the total variance of source samples (Figure 2). We assessed the first three PCA axes as two and three explained about the same percentage of variation, 14.8% and 13.6%. Ca, Se and U had strong positive relationships and K had a strong negative relationship with principal component 1 (Table 2). Cd and Mn had strong positive relationships with principal component 2. U had a strong positive relationship and Mn had a strong negative relationship with principal component 3. Only the 95% confidence interval ellipses for grassland and forest overlapped. Therefore, these two sources were pooled into upland as this generally reduces un-mixing model uncertainty (Koiter, Owens, et al., 2013).

Median concentrations of Ca, Cd, K, Mn, Se, Ti, and U significantly differed by sediment source ($p < 0.001$, except Ca which had $p = 0.016$) (Figure 3). Pairwise comparisons indicated Ca concentration was significantly

Table 1

Results of Tracer Selection Where Gray Indicates an Element Did Not Meet the Inclusion Criteria and Green Indicates an Element Met the Inclusion Criteria

Element	RT	KW	DFA	CR	CI
Ag	✓	✗	✓	88.1	−0.2
Al	✓	✗	✗	21.2	−0.4
Sb	✓	✗	✗	87.5	−0.2
Ar	✓	✓	✗	74.8	−0.2
B	✓	✗	✗	1	−0.4
Ba	✓	✓	✗	53.3	−0.2
Be	✓	✗	✗	3.4	−0.5
Ca	✓	✓	✓	48.2	−0.1
Cd	✓	✓	✓	29.3	−0.2
Co	✗	✗	✗	3.2	−0.4
Cr	✓	✗	✗	92.2	−0.5
Cu	✓	✓	✗	0.1	−0.4
Fe	✓	✓	✗	96.9	−0.3
K	✓	✓	✓	26.8	−0.2
Mg	✗	✓	✓	96.1	−0.4
Mn	✓	✓	✓	69	−0.6
Mo	✓	✓	✗	96.2	−0.4
Na	✓	✓	✗	50.2	−0.2
Ni	✓	✗	✓	21.8	−0.2
P	✓	✗	✓	87.2	−0.9
Pb	✓	✓	✗	92.1	−0.4
Se	✓	✓	✓	94.2	−0.2
Sn	✓	✗	✗	45.1	−0.3
Sr	✓	✓	✗	13.6	−0.2
Ti	✓	✓	✓	96	−0.2
Tl	✓	✓	✗	95.6	−0.4
U	✓	✓	✓	2.3	−0.1
V	✓	✓	✗	90.8	−0.3
Zn	✓	✗	✓	65.6	−0.3

Note. RT is boxplot-based range test, KW is Kruskal-Wallis H-test, DFA is stepwise discriminant function analysis, CR is consensus ranking and CI is conservativeness index. See Methods for details of inclusion criteria for each statistical test.

greater in upland sediment than the other three sediment sources ($p < 0.001$). For Cd, only canal and terrace sediment concentrations were significantly different ($p = 0.015$). K concentration in upland sediment was significantly greater than for the other three sediment sources ($p < 0.005$). Also, there was marginally higher K concentration in bank than canal sediment ($p = 0.083$). Mn concentration in upland sediment was significantly lower than bank or terrace sediment ($p < 0.007$). Se concentration was significantly lower in upland sediment than bank or terrace sediment ($p < 0.001$). Also, Se concentration was significantly higher in bank sediment than terrace sediment ($p = 0.004$). Ti concentration was significantly higher in bank than terrace sediment ($p = 0.004$), and Ti concentration in upland sediment was significantly higher in upland sediment than canal ($p = 0.010$) or terrace ($p < 0.001$) sediment. U concentration was significantly lower in upland sediment than in bank ($p < 0.001$) and canal ($p = 0.002$) sediment.

The conservativeness index and consensus ranking method (Table 1) indicated Se and Ti had high CR values (>94) and moderate CI indexes (−0.2), while Ca, Cd, Mn, and U had lower consensus values of 48.2, 29.3, 69.0, and 2.3. Further, the CI of Mn was large, −0.6, while the CI of Ca, Cd, and U was lower, −0.1 to −0.2. The consensus analysis suggested that Ca, Cd, Mn, and U were dissenting tracers, meaning that their exclusion produced a higher consensus and less likelihood of multiple model solutions (Lizaga et al., 2020b). Therefore, the tracers selected as the composite fingerprint were Se and Ti.

3.2. Validating the Source Apportionment Procedure

The global (overall) un-mixing model of virtual mixtures (Figure 4) had negligible bias, as indicated by the marginally positive MBE 0.001, and high accuracy in predicting actual values, as indicated by RMSE <0.13. NSE and KGE similarly indicated good model performance (precision and accuracy) as values were >0.75 (Table 3). Considering each sediment source separately, the model evaluation revealed a somewhat lower capability for estimating the contributions from canals than from bank, terrace, and upland sediment sources when contributions were >50%. This is supported by the lower (but still >0.5) NSE and KGE, and negative MBE. Overall, the virtual mixture results confirmed the reliability and accuracy of the modeled source contributions with the composite fingerprint.

3.3. Relative Source Contributions for Sediment Retained by Beaver Dams and BDAs

The un-mixing model clearly indicated that the sources of sediment retained by beaver dams were different than those for BDAs (Figure 5). On average, the model indicated that about 56% of the sediment retained by beaver dams originated from terraces, 23% from upland sources, 13% from beaver canal beds and 8% from stream banks (Figure 6). In contrast, about 89% of sediment retained by BDAs originated from stream banks, 8% from relict beaver canals, 3% from terraces and 1% from upland sources (Figure 6). There was low variation in sediment source apportionment amongst the BDAs. However, there was variation in sediment source apportionment amongst the beaver dams. The proportion of bank sediment retained by beaver dams in the more downstream position in the sequence (beaver dams 4 and 5 in Figure 5) was higher and the proportion of terrace sediment was lower.

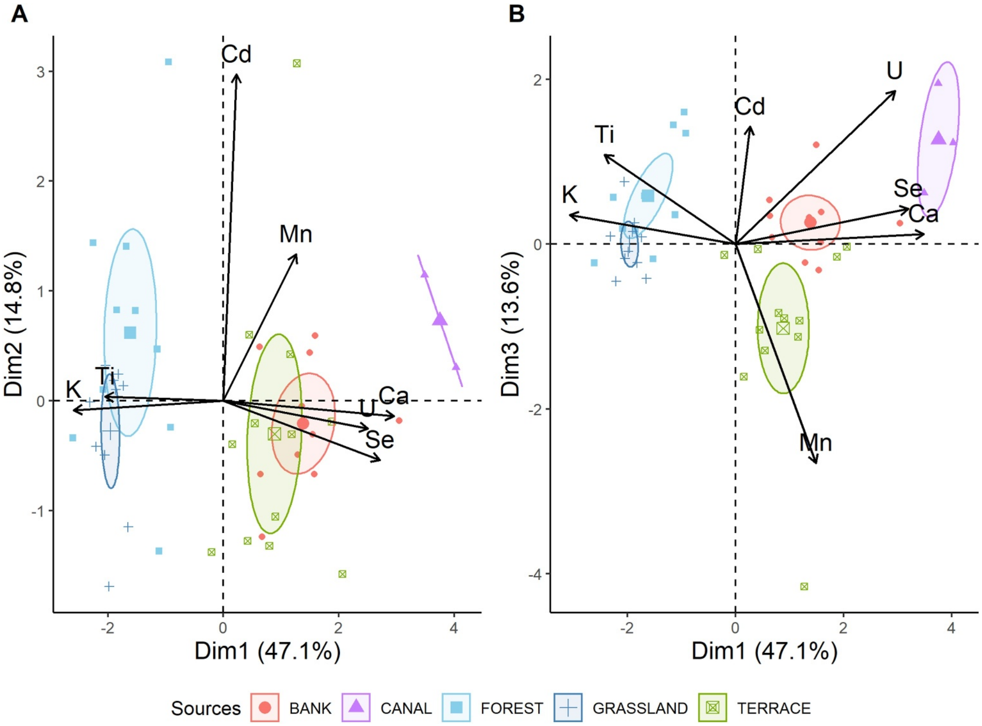

Figure 2. Scatterplot of source samples based on the first (Dim1) and second (Dim2) (a), and first and third (Dim3) (b) principal components derived by principal components analysis. Ellipses represent the 95% confidence interval and larger symbols indicate the mean.

4. Discussion

4.1. Utility of Sediment Fingerprinting for Identifying Sources of Sediment Retained by Beaver Dams and BDAs

Sediment fingerprinting reliably established the provenance of sediment retained by beaver dams and BDAs, demonstrating the utility of this approach. Testing the precision and accuracy of un-mixing models with virtual mixtures is an important step in the application of the fingerprinting method to determine the provenance of sediment retained by beaver dams and their analogs (Haddadchi et al., 2014). We relied solely on elements for the fingerprint analysis and found that the composite sediment fingerprint of Si plus Ti consistently had high accuracy and low uncertainty in differentiating riverine sediments from upland area sediments across a wide range of virtual source contributions. The composite sediment fingerprint also well differentiated streambank sediments from terrace sediments and terrace sediments from beaver canal sediments. Although, the model evaluation revealed a somewhat lower capability for estimating the contributions from beaver canals when they had a provenance >50%. The higher, but still reasonable model uncertainty for larger sediment contributions from canals is likely attributed to the small sample size of canal sediments. Beavers excavate canals to access distant food resources and so canals can be >0.5 km long (Grudzinski et al., 2020). We obtained composite sediment samples from all three beaver canals present at the south arm of the study site (Figure 1). The canals were long (>60 m) and heterogeneities in the elemental chemistry of their sediment along their length may have occurred. Pulley et al. (2017) showed that high-within source variability can introduce significant uncertainty into un-mixing model results. Investigation of longitudinal variation in the elemental chemistry of canal sediments would be useful for future studies to assess in advance of employing fingerprint analysis to determine the provenance of sediment retained by beaver dams.

Table 2
Loading Matrix of the First Three Principal Components Shown in Figure 2

Element	Dimension 1	Dimension 2	Dimension 3
Cd	0.039	0.897	0.381
Ca	0.500	−0.041	0.032
K	0.213	0.402	−0.709
Mn	−0.439	−0.025	0.095
Se	0.424	−0.076	0.495
Ti	0.459	−0.162	0.114
U	−0.347	0.012	0.289

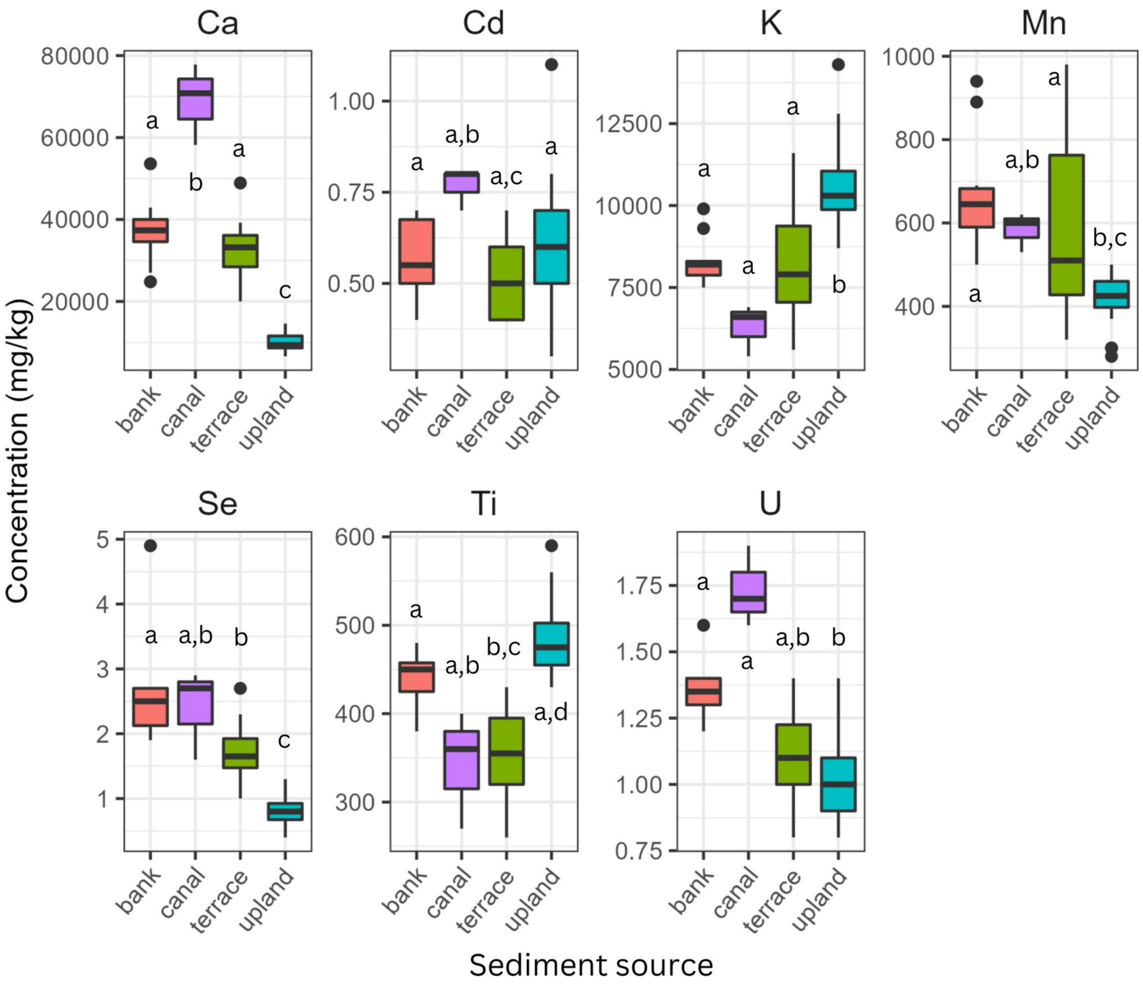

Figure 3. Boxplots of Ca, Cd, K, Mn, Se, Ti, and U concentrations by sediment source. Different letters indicate significant differences in elemental concentration amongst sources.

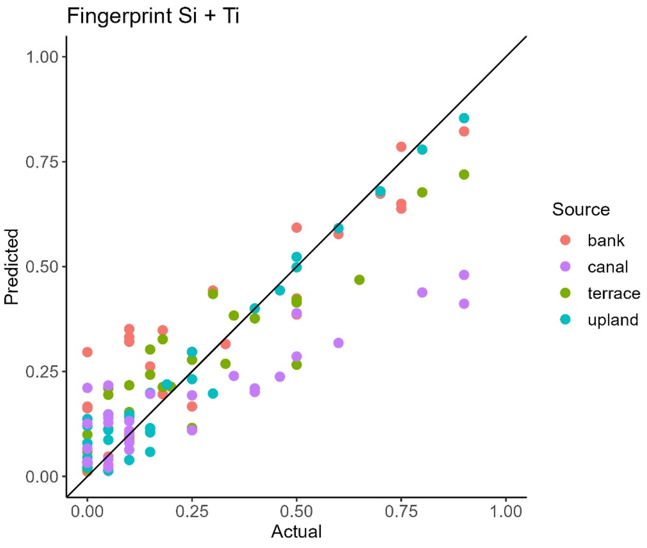

Figure 4. 1:1 plot showing the un-mixing model predicted decimal percent source contributions versus actual contributions for virtual mixtures.

Ti provided strong discrimination between the main groups of potential sources, with higher concentrations in the upland sediments, moderate concentrations in the stream bank sediments, and lower concentrations in the terrace and beaver canal sediment. Matrix-bound elements such as Ti, Si, Al, Zr along with the rare earth elements are likely to be the most conservative (Collins et al., 2020) and the finding of strong discrimination of Ti between sediment sources is consistent with the environmental behavior of this element. Because Ti has high resistance to weathering and low mobility it is often used to estimate the rate of weathering (Wan et al., 2019). Therefore, well developed and undisturbed soils often have higher concentrations of Ti in the upper than lower soil horizons (Kabata-Pendias, 1990). This is a likely explanation of why the highest Ti concentrations occurred in upland surface soils. Another contributing factor is that Ti is cycling in the vegetation (Burghelea et al., 2015; Lyu et al., 2017), limiting its leaching deeper into the soil layer, and limiting Ti concentration in eroded and transported soils.

Se concentrations are often low in river sediments in Alberta unless hard rock mining occurs in the watershed (Casey & Siwik, 2000). The identification of Se as a conservative tracer in the fingerprint selection process was unexpected. We had no instances of censored (below detection limit) data for Se,

Table 3
Un-Mixing Model Performance Metrics for the n = 30 Virtual Mixtures

	MBE	RMSE	NSE	KGE
Global model	0.001	0.124	0.773	0.753
Bank	0.044	0.121	0.808	0.678
Terrace	0.010	0.105	0.802	0.693
Upland	0.011	0.058	0.948	0.875
Canal	0.063	0.180	0.558	0.524

indicating a lithogenic source occurs in the catchment. Soil Se can be in naturally high concentrations in watersheds with shale-derived soils (Holmgren et al., 1993). The Paskapoo formation in the study area is composed of continental to alluvial plain deposits of mudstone, siltstone and sandstone with subordinate limestone and coal. On-site well driller reports available from the Government of Alberta at http://groundwater.alberta.ca/WaterWells indicate shale layers occur near the ground surface. Regional coals and shales have relatively high Se content (Hendry et al., 2015).

Se provided good discrimination of the main sediment sources that accumulated in beaver ponds, even those in close proximity. Se occurred in higher concentrations in beaver canal and bank sediment, moderate concentrations in terrace sediments, and lower concentrations in upland sediment. Lower concentrations in forest and grassland soils may occur due to its recycling within trees and the primarily oxic surface organic matter (Tuttle et al., 2014). Se concentrations were distinct for beaver canal versus terrace sediments even though the canal was excavated into the terrace. Lidman et al. (2011) report that elemental Se precipitates in riparian soils under anoxic conditions below the seasonal low water table (Yabusaki et al., 2017), and that depletion of atmospherically deposited Se occurs on riparian land surfaces. This suggests that Se concentration increased with depth in the terrace. Beavers excavated canals approximately 0.5 m deep into terraces in the Pine Creek watershed where the seasonal mean water table is approximately 0.3 m deep (Munir & Westbrook, 2021a). Therefore, the canals intersected the water table and anoxic soils, and were nearer to the parent material.

The sediment fingerprinting approach allowed us to establish the provenance of sediment retained by beaver dams and BDAs in this watershed and provided an improved understanding that was not possible without fingerprint methods. This approach holds promise for identifying sediment source types for other beaver dam/BDA studies. Although we used elements in this analysis, a wide range of tracers have been used in sediment fingerprinting, including radionuclides and mineral magnetism (Koiter, Owens, et al., 2013). Other possible tracers include specific stable isotopes, color properties, eDNA or microbial community fingerprints (Batista et al., 2022; Evrard

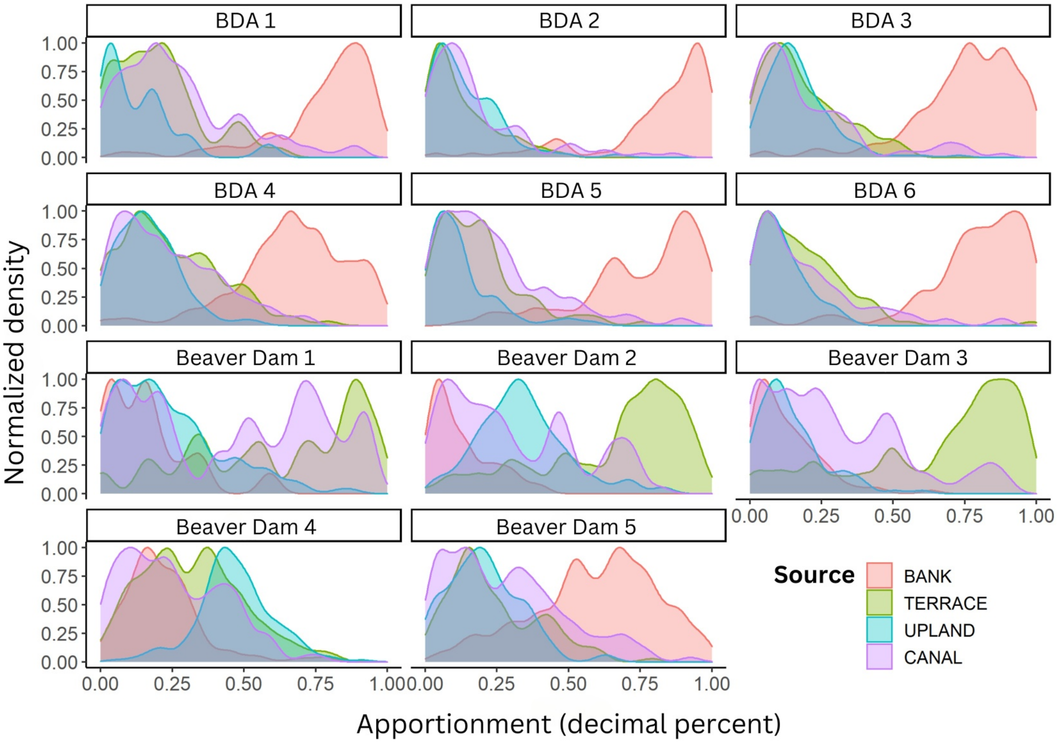

Figure 5. Probability distributions of the fractional contribution of each source to the sediment retained behind the six beaver dam analogs and the five beaver dams as determined by the un-mixing model. Model goodness-of-fit was >0.82 in each case.

et al., 2019; Sun et al., 2022). Given the wide-range of beaver distribution, the ultimate combination of tracers selected for use in mixing models to distinguish watershed sources of sediment retained behind beaver dams or BDAs should reflect the land use, geologic parent materials, climate and erosional history of the watershed. We recommend that future studies explore combining fingerprinting of sediments with measures of the thickness of those layers (Lamba et al., 2015) to provide an understanding of erosional processes in the watershed and what ecosystems are producing the sediments retained by beaver dams and BDAs.

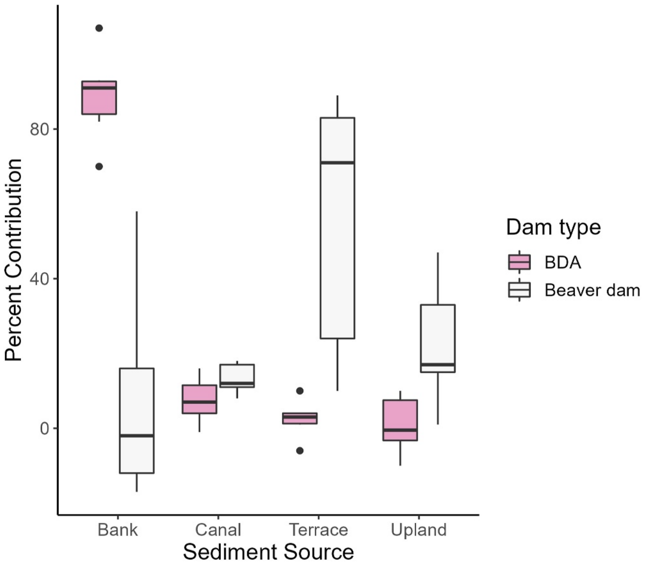

Figure 6. Variation in mean sediment source contributions of sediment retained by beaver dam analogs and beaver dams.

4.2. Different Sediment Source Apportionment for Beaver Ponds and BDA Ponds

Our un-mixing model indicated that about 55% of the sediment retained by beaver dams originated from terraces, 23% from upland sources, 13% from beaver canals and 8% from stream banks, addressing the question that has persisted for 30 years of what proportion of the sediment behind beaver dams is fluvially transported versus supplied via beaver activity such as bank excavation (Butler & Malanson, 1995). The un-mixing model results also confirm that the sediment retained by beaver dam originates from different and more diverse sources than sediment retained by BDAs (Figure 7). Beavers are known geomorphic agents (Butler, 1989) that actively and passively erode sediment that is delivered to and retained by their ponds. Beavers construct and maintain dams by placing woody branches and excavated sediment and rocks, and passively capture wood and sediment entrained in the flowing stream (Blersch & Kangas, 2014). Once built, beaver dams can cause overbank flooding that inundates terraces (Westbrook et al., 2006). Our observations indicate that all five studied beaver dams created terrace inundation that eroded the surface sediment. This degree of lateral hydrologic connectivity was not created by the BDAs. Terraces have higher hydraulic roughness than channels and slow the flow of beaver-dam directed water across them. This can induce sediment deposition at low flows (John & Klein, 2003), but during high flow events, terrace sediments can be eroded (John & Klein, 2003) and transported to the channel where they are captured behind beaver dams. Beavers also excavate extensive canal networks that they use for mobility and food acquisition (Berry, 1923). Beavers transport excavated riparian soils from canals to dams and ponds while the rest is deposited in adjacent levees and is susceptible to erosion into streams (Butler & Malanson, 1995; Grudzinski et al., 2020). The un-mixing model indicates that the predicted contribution of 13% canal sediment could result from an actual contribution of 0%–26%, considering the model average error (RMSE) of 0.13. It is unlikely that the canal sediment contribution was zero because at the time of our sediment sampling three beaver canals longer than 60 m were present at the study sites. As these canals were 0.5–1.0 m deep, this is a collective displacement of at least 90–180 m^3 of sediment. Therefore, although the areal canal coverage in the watershed is small (<0.0001%), our model suggests that canal excavation has an outsized influence on the composition of sediment retained by beaver dams. Overall, we found that beaver activity account for about two-thirds of the

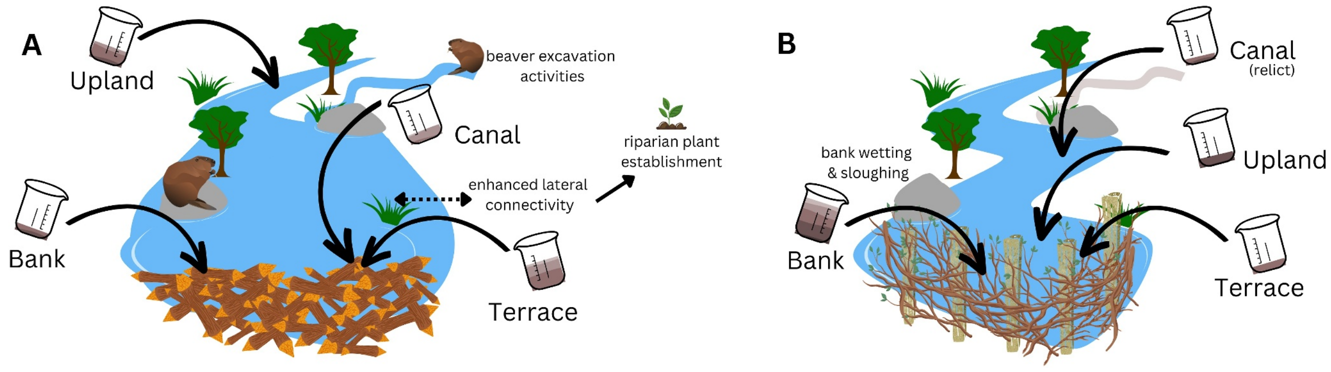

Figure 7. Conceptualization of sources of sediment retained by panels (a) beaver dams and (b) beaver dam analogs.

sediment stored behind beaver dams at our site, raising important questions of whether the volume of sediment accumulated by BDAs, especially those installed in landscapes without relict beaver features, will be less than beaver dams over comparable time periods. River scientists should therefore direct their attention to coupling sediment fingerprinting with measures of sediment volumes in paired beaver- and BDA-impacted systems to clarify the role of beavers as a major stream geomorphic agent. Such work would the provide the insights needed to support successful beaver-based stream restoration.

We documented that position within a sequence of dams played a role in sediment provenance (Figure 5). Downstream ponds are more stable than upstream ponds as they are buffered from high energy streamflow by the upstream ponds (Naiman et al., 1986; Westbrook et al., 2020). Sediment storage decreases downstream within some, but not all beaver dam sequences (Butler & Malanson, 2005; Puttock et al., 2018; Stefan & Klein, 2004). If position in the beaver dam sequence was the only change in sediment provenance we would expect to find a declining proportional contribution of upland sources in downstream ponds. Instead, we found that ponds in downstream positions had a greater proportional contribution of bank sediments, greater than the model error, without reductions in the proportional contributions of upland sediments. The sediment source that decreased to produce this pattern was the terrace sediment. This trend was observed only for beaver dams, not for BDAs. An increased relative proportion of bank sediment and decreased relative proportion of terrace sediment in downstream beaver ponds may result from in situ sediment redistribution by beavers rather than variations in passive capture of suspended sediment. Beavers develop stream bank and tunnel slides where they frequently exit or enter the water. This can increase locally derived sedimentation into the stream (Meentemeyer et al., 1998). Beaver burrowing also can cause bank slumping into streams (Butler & Malanson, 1994). A higher proportion of bank sediments in the downstream ponds might be because this pond was built first in the series (in 2015) or due to greater beaver activity in downstream than upstream ponds, although observations of beaver activity are needed for confirmation.

We hypothesized that sediment retained by BDAs would originate primarily from upstream catchment erosion. However, we found that it originated primarily from streambanks, indicating our hypothesis underestimated the importance of bank erosion in supplying suspended sediment to the stream following BDA installation. A key aim for the use of BDAs is often to promote streambed aggradation, achieved by reducing streamflow velocity (Lautz et al., 2019) and expanding stream area above BDAs (Vanderhoof & Burt, 2018; Weber et al., 2017). Pond formation upstream of in-stream structure also leads to redirection of streamflow toward banks (Munir & Westbrook, 2021a). Wetting of bank materials decreases their cohesion that can increase susceptibility to sloughing and erosion (Bull, 1997). Riparian vegetation can act as a stabilizing force for wet streambanks, reducing the delivery of bank sediment to the channel by increasing bank soil cohesion through root reinforcement (Micheli & Kirchner, 2002). However, streams without beavers typically become incised (Pollock et al., 2007), which reduces the frequency of riparian flooding and diminishes riparian vegetation cover and production along channel margins (Fairfax & Small, 2018; Merritt & Cooper, 2000; Wolf et al., 2007). Streambanks with degraded vegetation have the potential, when wetted, to become an important source of suspended sediment supply to a stream (Bull, 1997). The north arm of Pine Creek has incised due to the loss of beavers (Munir & Westbrook, 2021a). As a result, most willows have died and been replaced by upland grasses, a change that can reduce bank stability (Polvi et al., 2014). The 0.36–0.46 m rise in stream stage associated with the BDA installation produced a short term wetting of streambanks (Munir & Westbrook, 2021a), and we observed bank sloughing in spring 2018 following the freshet and moderate rainfall events. Bank wetting can reduce streambank cohesion and increase bank sloughing, and may have contributed to the high proportion of sediment originating from localized erosion of streambanks and retained by BDAs. Some of the bank contribution may be from erosion of banks upstream of the BDAs. Sediment fingerprinting is not well suited to differentiate local versus upstream bank contributions to BDA-retained sediments in watersheds the size of the north arm of Pine Creek as Belmont et al. (2014) found little variation in the chemical composition of banks across a small catchment. Therefore, alternate methods would be needed to shed light on local versus upstream bank erosion contributions to BDAs. Our observations might also help explain observations by Davis et al. (2021) of net erosion near BDAs during their first year after installation. While our sediment source apportionment is only for sediment retained by the BDAs in their first year, this is an important period for riparian processes (e.g., Munir & Westbrook, 2021a) as little is known about temporal changes in vegetation development and streambank cohesion created by BDAs. Orr et al. (2020) found that willow cuttings planted near BDAs in Oregon, USA had considerably higher growth rates in the first 6 months than those planted elsewhere along the channel margin, which could enhance long term bank stability. Long term willow growth near simulated beaver structures in Yellowstone National Park, USA also had increased growth at a rate of 15–20 cm/yr from the first year (Bilyeu et al., 2008; Hobbs et al., 2024). This underscores the need for long term studies of sediment source contributions to BDAs as hydrological and ecological recovery occurs.

5. Conclusions

This study demonstrates a novel use of an increasingly important method in hydrogeomorphology—sediment fingerprinting—with implications for stream restoration. Sediment fingerprinting was used to distinguish sediment source contributions to beaver dams and the most commonly used type of beaver mimicry structure, BDAs. We tested the reliability of the approach at the Pine Creek watershed, located on the eastern slope of the Canadian Rocky Mountains just southwest of Calgary, Alberta. Virtual mixture tests revealed that sediment fingerprinting reliably established the provenance of sediment retained by beaver dams and BDAs. We also provided insights into the persistent question of what proportion of the sediment behind beaver dams is fluvially transported versus supplied via beaver activity such as bank excavation (Butler & Malanson, 1995) by showing that BDAs do not replicate the sources of sediment retained by beaver dams. Beaver activity including canal building and sediment excavation creates more diverse geomorphic effects resulting in more diverse sediments retained by their dams than BDAs. We worked in one watershed to develop and test methods and our hypothesis. But as more BDAs are installed to simulate the channel response of beaver dams (Pollock et al., 2014), we recommend additional testing of sediment fingerprinting in watersheds with contrasting bedrock, landforms, land uses, sediment fluxes, and beaver and BDA history. It would also be helpful for future studies to pair measurements of sedimentation in beaver ponds with sediment fingerprinting and observations of beaver pond occupancy (Hood, 2020) to more fully understand how biotic and abiotic variables interact to regulate pond sediment retention throughout the life of a pond and provide the insights needed to support successful beaver-based stream restoration.

Data Availability Statement

Data sets for this research are publicly available in Westbrook and Cooper (2024) via https://doi.org/10.20383/103.0938.

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