

Best Restoration Practices: Do BDAs Mimic Inundation Patterns of Natural Beaver Dams?

KEYWORDS Beaver dam analogues (BDAs), beaver-augmented BDAs, hydrology, sediment grain size, Trail Creek

ABSTRACT

Watershed degradation in the Western United States is a continuing issue under climate change. The headwaters to the Colorado River in the Rocky Mountains are experiencing dryness, altered chemistry, and flashiness due to climate change. Management practices involving artificial beaver dams (BDAs) have been used to counteract these issues. Though well intentioned, lack of monitoring has led to a lack of understanding of how these BDAs are impacting streams. There are uncertainties of how inundation patterns behind BDAs will change in shape, width, depth, and sediment deposition after a beaver further engineers the dams. We sampled six BDA ponds and beaver-augmented BDA ponds to compare a variety of morphological characteristics related to hydrology. The beaver-augmented BDA ponds were significantly deeper than the BDA ponds since continuous engineering on the dams allows for more water impoundment and therefore a deeper pond. The BDA ponds had lower surface areas than the beaver-augmented BDA ponds since they had significantly shorter dams, and the beaver-augmented ponds were also rounder. There were not significant differences in the sediment grain size between treatment types since the beaver-augmented BDA ponds are so new. By comparing BDA habitats to beaver dams, this study improved understanding of the impacts of restoration using BDAs, and can be used in future conservation efforts.

INTRODUCTION

Watershed degradation has become a prominent issue in the Western United States due to a legacy of anthropogenic effects, such as livestock grazing, logging, mining, road building, and climate change (U.S. Forest Service). As a result of changing climate in the Upper Colorado River Basin, peak streamflow runoff is occurring earlier in the season, while summer base flow is decreasing due to earlier snowmelt (Ashton et al. 2010). This not only impacts the quantity of water in the summer, but its quality (Ashton et al. 2010). Erosion increases due to an earlier peak flow, adding pollutants and suspended sediments which alter water chemistry and affect already sensitive ecological systems. Water tables may decline due to lower baseflow, creating a flashier, hydrologic system overall (Poff et al. 2002). Recent science shows groundwater losses in tributaries to the East River in Colorado due to climate change impacting precipitation regimes (Carroll et al. 2024). In response to stream degradation and drying, there has been an increase in stream restoration projects involving beaver dams. These “nature-based” restoration practices help to better regulate erratic streamflow by creating wetland conditions that aggrade sediment and increase inundation and connections to floodplains, providing habitat for the sensitive species that inhabit these ecosystems (Charnley et al. 2020).

Commonly, nature-based restoration practices across the West have been centered around human-made beaver dams, or beaver dam analogues (BDAs). BDAs are built using materials that naturally occur in the area: posts are put in, willow branches are woven between the posts, and mud, rocks and grasses are used to fill the gaps. They are constructed to replicate natural beaver dams, with the intention of retaining and creating slow moving water to counteract channel erosion (Wade et al. 2020). BDAs are meant to connect the stream to the floodplain like a natural beaver dam would, and to increase the surface water storage of the system (Pearce et al. 2021). When these dams are put in place, they widen incised streams as flooding and sedimentation occur. Wetland plant species, such as willows and sedges, are reintroduced and their roots bind to the substrate, further preventing erosion (Pollock et al. 2014). Past stream restoration practices, such as cross-vanes and j-hooks, haven't effectively mimicked natural processes of wetland management, which has led to the use of BDAs (Lautz et al. 2019). However, despite their popularity, BDA-based restoration projects rarely undergo post-restoration monitoring, and thus measures of their effectiveness are largely lacking (Colley 2022). Therefore, monitoring these structures is imperative such that land managers and environmental consultants can ensure they function as intended to effectively restore riparian ecosystems in the West.

There is limited knowledge of the surface area and depth of the ponds created by BDAs, and further how these metrics change when beaver enter the system and take over management of the dams. Since monitoring these patterns is uncommon, comparisons need to be made between different treatment types to understand effects on the hydrology and geomorphology of the area (Colley 2022). Measuring the surface area, depth, and sedimentation of ponds formed by both BDAs and beaver-augmented BDAs are also important for determining how crucial the eventual addition of beaver to the restoration site may be. Since BDAs reduce water velocity like natural beaver dams, sedimentation does occur behind these dams (Grudzinski et al. 2022). However, grain size may be impacted by beaver augmentation since these improved dams will likely further reduce water velocity and allow for deposition. Increased pooling in beaver-augmented sites and slightly higher water velocities in BDA sites may result in larger sediment grain size in BDAs ponds than beaver-augmented BDA ponds (Scamardo and Wohl 2020). Understanding the ways in which aquatic systems respond to BDAs could counteract habitat fragility and water insecurity in the face of climate change (Fillion et al. 2024).

The objective of this research is to characterize the inundation patterns behind both beaver-augmented BDAs and BDAs. In the Elk Mountains of Colorado, Trail Creek includes BDAs, and beaver-augmented BDAs, providing an ideal study site for comparing the effects of artificial beaver dams on inundation patterns. Here, monitoring the surface area and depth of inundation behind dam structures will be possible. We predict that BDA ponds will be narrower, deeper, and shorter in length than beaver-augmented BDAs due to the width and positioning of the BDAs. Since BDAs are not monitored and their inundation isn't consistently engineered as beaver-augmented BDAs are, it is hypothesized that BDA ponds will be narrower since flow is

maintained, they will be deeper, since there isn't as much sedimentation due to higher flow rates, and the ponds will be shorter since higher flow rates will counteract inundation efforts.

METHODS

Site Description

This study took place at Trail Creek, a second order tributary to the Taylor River in the Elk Mountains of Colorado (approximately 38.902058, -106.620249). The Taylor River is a part of the Upper Gunnison River watershed, and Trail creek is located in a montane sagebrush meadow with an elevation of ~10,764 feet. The creek is a part of the Gunnison National Forest and is surrounded by aspen-conifer forests (U.S. Forest Service 2024). The bedrock of the area is Precambrian granite as well as metamorphic volcanic rock with glacial sediment and alluvium downslope (ASCC 2022). Seasonal snowmelt heavily contributes to the hydrology of Trail Creek and surrounding streams. These streams flow into the Taylor River, which meets the Gunnison downstream and eventually joins the Colorado River.

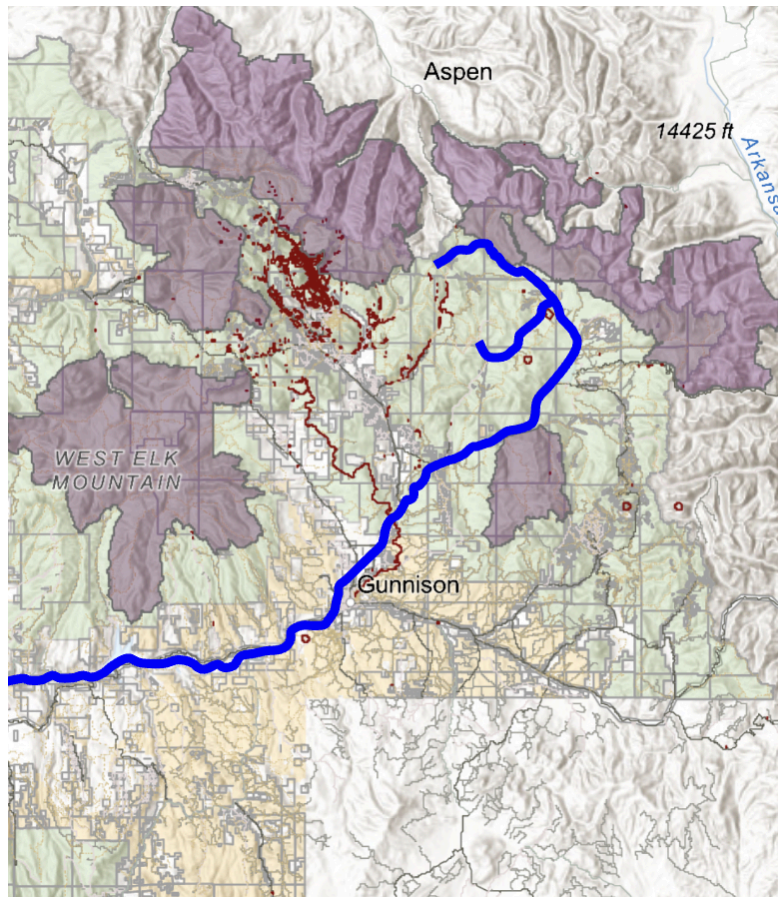


Figure 1. Map of Elk Mountains in Colorado (purple). Red represents RMBL study sites. The blue line is the Taylor River, with a small blue line showing the Trail Creek tributary to the Taylor River.

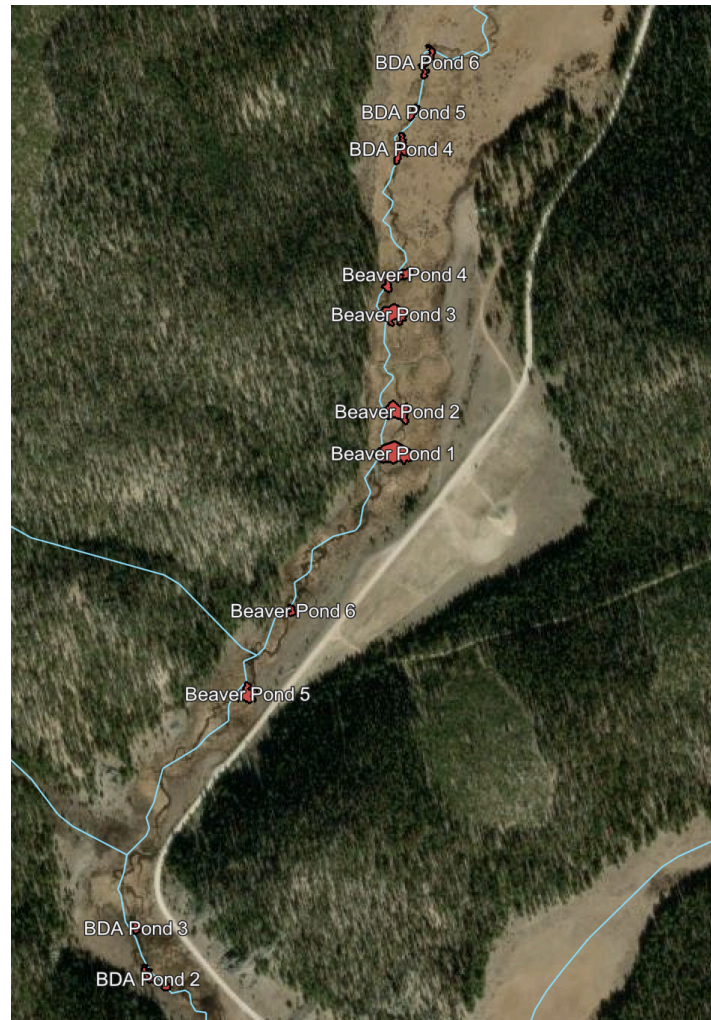


Figure 2: Ponds sampled at Trail Creek

At Trail Creek, twelve ponds were chosen for study. Six ponds were unaltered BDAs (hereafter referred to as BDAs) and six were beaver-augmented BDA ponds. Of the BDA ponds, three were upstream of the beaver-augmented section and three were downstream. No selected sites were directly adjacent to one another; there was always at least one pond in between. Beaver-augmented ponds had to have BDA dam structures that had been added to by beaver (with materials such as willows, mud, sedge, and rocks), and some were even extended laterally, adding on to the original BDA. BDAs with partial beaver augmentation were not chosen. BDA pond sites had beaver additions to the dam.



Figure 3. Image to the left is an example of a beaver dam as compared to dam to the right, an example of a BDA at Trail Creek.

Data Collection

To measure the shape of inundation behind dam structures, the 60 cm accuracy Trimble DA2 GPS system was used to map a polygon of each beaver pond and BDA pond. Using the perimeter data, a surface area was calculated in order to compare surface areas between pond types. The length of each dam structure was measured with a 100 m tape, as well as mapped with the Trimble DA2 GPS system. The total length of the beaver-augmented BDAs was measured, and the length of the original BDA within each beaver-augmented BDA was recorded. When a pond was formed by multiple dam structures, the length of each structure was measured and these lengths were added together in order to determine the total damned portion of the pond. BDA length was determined by measuring the distance from the left most post the streambed to the right most post put in the streambed. Beaver-augmented BDA measurements began and ended where the beavers started placing sedge, mud, and rocks.

Depth measurements were taken randomly throughout the ponds where the main channel (thalweg) of the stream existed prior to increased inundation. Depth measurements were not taken in canals connected to the pond or in inundated floodplain areas. At each pond, 20 depth measurements were taken with a meter stick. When the depths were greater than one meter, two meter sticks were used to measure the depth. Average depth for each pond was then calculated and the average depth was compared between treatment types.

A Wolman pebble count was conducted at each pond. This was done by randomly selecting 100 pebbles from each pond and measuring their size using a gravelometer. This was randomized by selecting the pebble under the right big toe of the measurer at each step taken while walking in the pond. When the pond was too deep to reach the bottom to grab the pebbles by hand, a D-net was used to collect substrate. The pebbles that were under the right big toe were

kicked into the D-net and then measured to keep the collection randomized. From these pebble counts, median sediment grain size was calculated for each pond.

Data Analysis

All data was analyzed using the RStudio software (R Core Team 2024). Dependent variables, such as dam length, pond surface area, pond perimeter, water depth, and median sediment grain size, were tested as a function of treatment (BDA and beaver-augmented BDA). This was done using t-tests, specifying if the variance was equal or unequal per variable. Variables that were not normally distributed were logged to meet test assumptions.

After measuring pond perimeters, a bounding box was created for each pond to better understand dimensional ratios. This was done in RStudio using the ‘terra’ package (Hijmans 2025). The bounding box was applied by creating a vector object and then calculating the smallest possible box that could hold the vector object. The length and width of the bounding boxes were then calculated and plotted to visualize each pond. Bounding box ratios were also tested by treatment using a t-test.

RESULTS

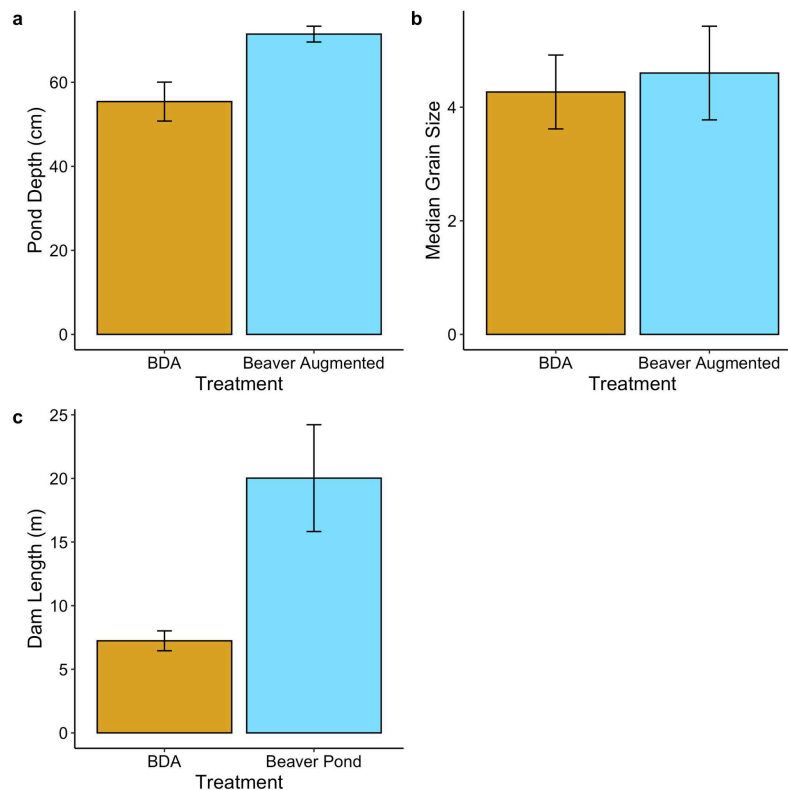


Figure 4. Graphs with results for Pond Depth (cm) by Treatment (a) were significant with BDAs being significantly shallower, and beaver-augmented BDAs being significantly deeper. Median Grain Size by Treatment (b) was not statistically significantly different. Dam Length by Treatment (c) was significantly different with BDAs being shorter than beaver-augmented BDAs..

Testing for differences in pond depth revealed that average depth was significantly different by treatment (T-test, $t = -3.21$, $p\text{-value} = 0.01$). The beaver-augmented BDAs were deeper with a mean pond depth of 71.47 cm and BDAs were shallower with a mean pond depth of 55.41 cm (Figure 4a). Median grain sizes between BDAs and beaver-augmented BDAs were not significantly different. The mean grain size in BDAs was 4.26 mm and the mean grain size in beaver-augmented BDAs was 4.60 mm (Figure 4b). Dam length of BDAs compared to beaver-augmented BDAs were significantly different (Two sample t-test, $t = -3.59$, $p\text{-value} = 0.005$). Total dam lengths of beaver-augmented BDAs were greater than those of BDAs (Figure 4c).

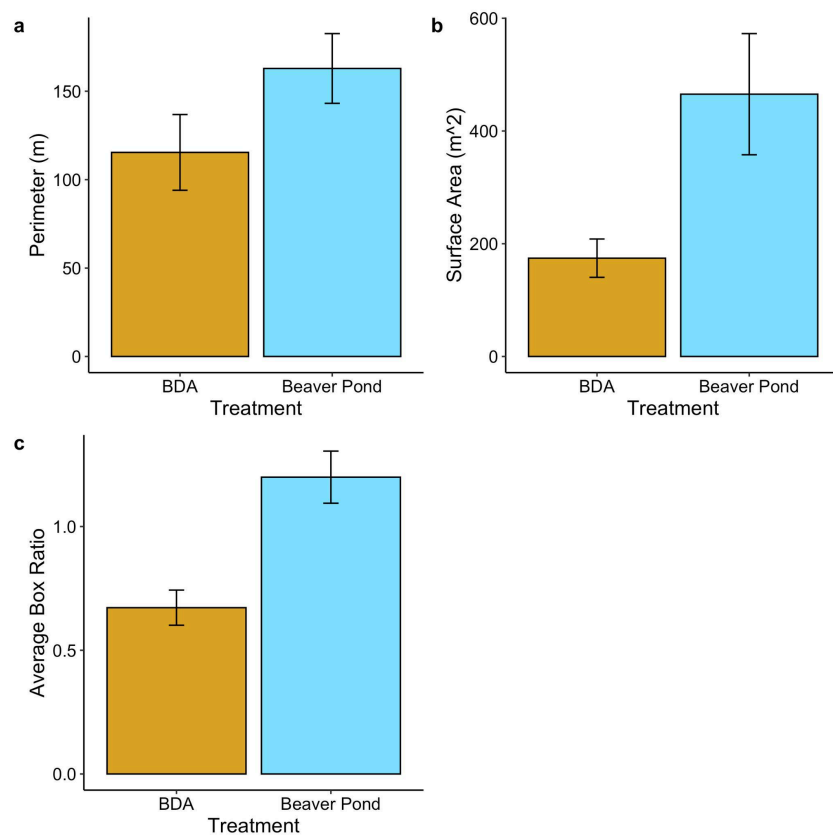


Figure 5. Graphs with results for Perimeter (m) by Treatment (a) were not statistically significantly different. Surface Area (m²) by Treatment (b) was significantly different between treatments with beaver-augmented BDA ponds having greater surface areas than BDA ponds. and Average Box Ratio by Treatment (c) was significantly different between treatments with BDA ponds having a smaller bounding box ratio than beaver-augmented BDA ponds.

There were no differences in perimeter among the BDAs and beaver-augmented BDAs . The mean perimeter for BDA ponds was 115.4 m and the mean perimeter for beaver-augmented BDA ponds was 162.9 m (Figure 5a). Pond surface area differed significantly by treatment (T-test, $t = -2.59$, $p\text{-value} = 0.027$). Beaver-augmented BDAs had a greater average pond surface

area with a mean surface area of 5.97 m², and BDAs had a smaller average pond surface area with a mean surface area of 5.07 m² (Figure 5b).

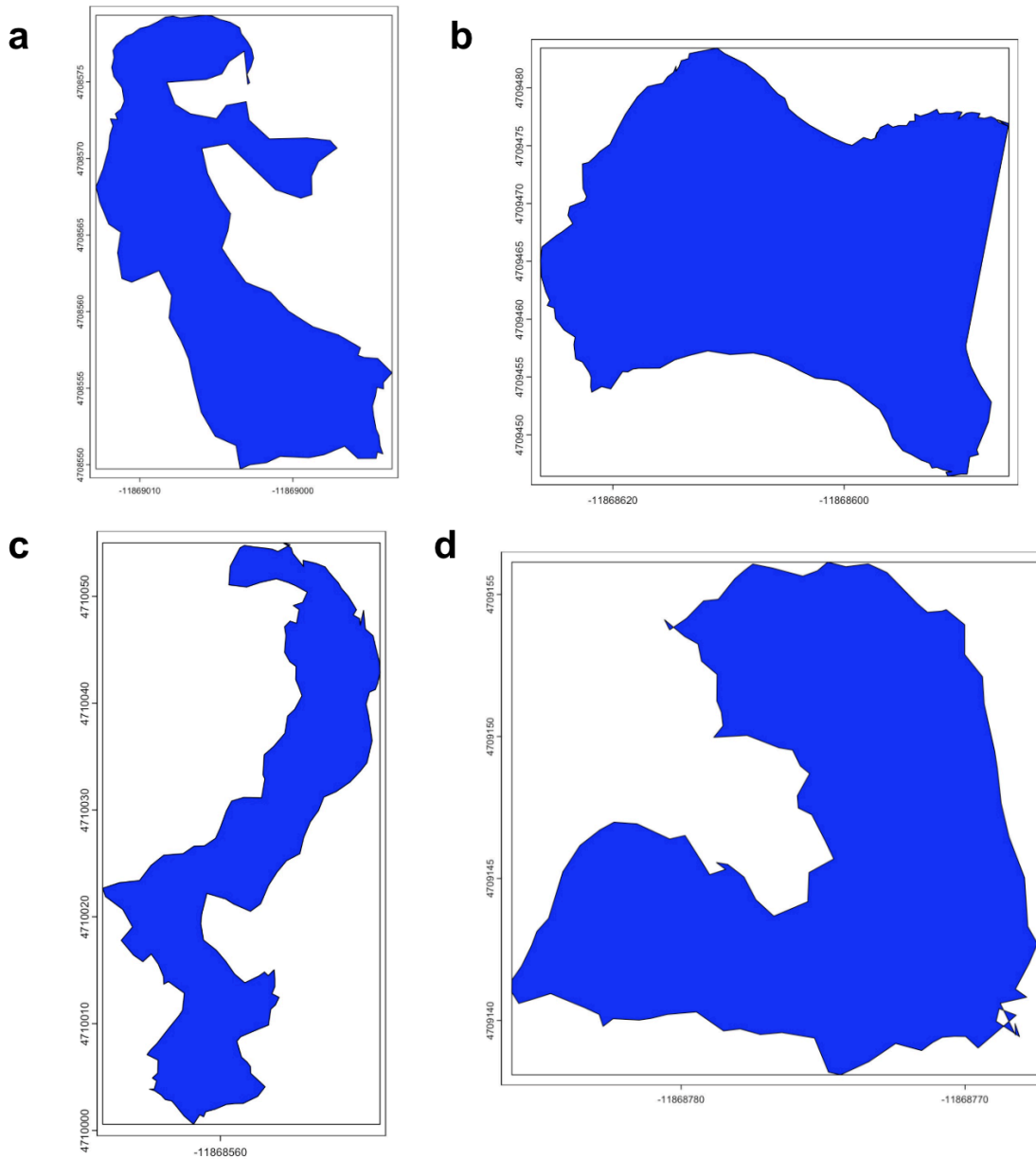


Figure 6. Image a: BDA pond 2 inside of bounding box, pond has a low bounding box ratio, making it more rectangular and irregularly shaped compared to image b: beaver-augmented BDA pond 2 inside of bounding box, pond has a high bounding box ratio making the box more square and pond more circular and regularly shaped than BDA pond 2. Image c: BDA pond 6 inside of bounding box, pond has a low bounding box ratio and is longer with a more rectangular box compared to image d: beaver-augmented BDA pond 6 inside of bounding box with a high bounding box ratio, meaning a more circular pond shape.

We also tested the dimensions of the ponds. The ratio of dam length to total pond perimeter did not differ significantly between treatments. The difference in ratio of dam width to pond area between treatment types was also not significant. The bounding box ratio between the two treatment types was statistically significant, with a lower bounding box ratio for BDA ponds (Two sample t-test, $t = -4.1528$, $p\text{-value} = 0.002$). The mean bounding box ratio for BDA ponds was 0.672 and for beaver-augmented BDAs it was 1.199 (Figure 5c). A bounding box ratio value of 1 indicates equal dimensions, indicating a square or circle, therefore beaver-augmented sites had more circular shapes, and BDAs more rectangular (Figure 6).

DISCUSSION

The goal of this study was to understand how inundation patterns may differ between BDAs and beaver-augmented BDAs. We found that beaver-augmented BDA ponds were deeper than BDA ponds. This is the opposite of what we had hypothesized, that BDA ponds would be deeper than the beaver-augmented BDA ponds. We had thought that BDA ponds would be deeper, since these ponds retain more flow than beaver-augmented BDA ponds do, we had assumed that this flow would cut into the streambed, causing a deeper pond. The results demonstrated the contrary, however, this is because beaver-augmented BDA ponds are hosts to beavers who will continue to engineer their dams and perform general upkeep to maintain their ponds. In order to survive, beavers need a deep enough pond to act as a refuge and allow for an underground entrance to their lodges (Baker et al. 2003). As beavers add to their dams, the dams get higher and cause more inundation, resulting in deeper ponds (Scamardo et al. 2020). These results demonstrate that BDAs are not as effective as beaver-augmented BDAs, since BDAs are not continuously monitored and plugged to produce a deeper pond and a greater area of inundation. In areas where leaky structures could be an issue, BDAs could be improved with continuous maintenance by humans until the beavers find the habitat suitable enough to take over.

Beaver-augmented BDA ponds also had a significantly greater surface area than the BDA ponds at Trail Creek. The BDA ponds at Trail creek still maintain some flow since the dams have more holes. This flow doesn't allow for as much water build up behind the dams as compared to the beaver-augmented BDAs. The beaver-augmented BDAs are able to increase inundation behind the dam structure since it is continuously being built. While at Trail Creek, beaver activity was observed at the beaver-augmented BDAs because sedge, rocks, mud, and willow branches were being placed extending the BDA on either side of the posts. The willow branches observed still had green leaves and had white marks on the branches where the willow was freshly chewed off. Flow reversal is what causes ponding in the riparian environments and is caused when dams are put in place. It elevates the water table in areas where flow is reversed, so much so that it appears as though there is not a drought taking place, because the water is high enough to reach riparian vegetation (Munir et al. 2021). This was observed at Trail Creek as well, in the dammed section the water was high in the riparian vegetation, and in the untreated upstream part of the creek, it looked like we were in a drought.

Due to the continuous engineering of the beaver-augmented BDAs, these dams were found to be significantly longer than the BDAs. BDA structures at Trail Creek are limited to the length that they were when they were installed, and sometimes have flow skirting around the edges. The beaver-augmented BDAs are not limited by the left and right most posts, and therefore have the potential to grow as beaver see fit. The results support the hypothesis that the beaver-augmented BDAs will be longer than the BDAs since beaver activity increases the lengths. In contrast, perimeters of BDA ponds and beaver-augmented BDA ponds were not significantly different. This could be due to BDA ponds having more irregular shapes and therefore having a larger perimeter without storing as much water. Beaver-augmented BDA ponds have similar length perimeters to BDA ponds but significantly larger surface areas. It is more common for beaver dams to have greater surface areas and larger floodplains than BDA ponds (Scamardo et al. 2020). With this information, as well as our understanding of the beaver-augmented BDA at Trail Creek, it makes sense the beaver-augmented BDA ponds would have larger surface areas.

The ratio of dam length to total pond perimeter and to pond surface area were not significantly different by treatment. This may mean that the perimeter, surface area, and overall shape of these ponds may be less related to the dam length and more related to the curvature of the dam and other landscape features (Ronnquist et al. 2021). There are a lot of factors that influence beaver dams that were not studied in this experiment such as substrate, vegetation cover, stream flow, and overall topography (Ronnquist et al. 2021). In the future, these factors should be examined in order to understand how beaver dams are impacted by surrounding factors.

Another way in which the inundation pattern differs between the two treatment types is in their bounding box ratio. When the pond shape is placed in a box, the squareness or rectangularness of the box is measured in a ratio and this determines how circular or irregularly shaped the ponds are. The bounding box ratio of the BDA was significantly lower than that of the beaver-augmented BDAs, this means that the BDA ponds were longer and less circular than the beaver-augmented BDA ponds. These results support the hypothesis that inundation pattern differs between the two treatments and suggests that BDAs do maintain a certain amount of flow since their pattern trends toward a narrower shape. The reason why these BDA ponds are so narrow and long is because they are not altered by beaver activity, and therefore, the inundation does not reach far beyond the thalweg of the ponds. One study by Wade et al. showed that BDAs and natural beaver dams that were similar in size appeared to have the same type of “hydrodynamic mechanism” (Wade et al. 2020). Understanding this further supports the understanding that these types of dams create different inundation patterns due to the sizes of the dams and how often they are maintained. If dams are not maintained, their flooding also doesn’t extend far beyond the thalweg of ponds. Impacts on streamflow by BDA structures was studied by Munir et al. and BDAs were found to have little effect on the hydrologic connectivity between the stream and the floodplain, meaning that the BDAs in certain scenarios do not inundate far beyond the natural shape of the stream (Munir et al. 2021). This was the case for Trail Creek as

well since the pond shapes, as demonstrated by the bounding box ratios, were narrower and followed the stream shape more than the beaver-augmented BDA ponds did.

Median grain size also did not differ significantly between treatment types, going against the hypothesis that there would be larger grain sizes found in the BDA ponds than in the beaver-augmented BDA ponds. Similar fluvial processes are likely occurring in these two different treatment types, even though the beaver-augmented BDAs are deeper. This could be because the beaver augmentation to these ponds is fairly recent and flow has not been altered for long enough to allow for enough aggradation of fine sediment over the original streambed (Rees et al. 2024). This would be interesting to study in the future, as more time with beaver activity could allow for this sediment to collect at the bottom of these ponds and for their median sediment grain size to be smaller than the median sediment grain size of the BDA ponds.

Overall, our hypotheses were supported by these results. BDAs do seem to be bringing beavers back to Trail Creek, so in a way they are an effective form of restoration, however, without the help of the beavers, these dam structures do not effectively mimic the inundation patterns of natural beaver dams like they are intended to. The installation of these dams either needs to be innovated, or there needs to be consistent monitoring and building on to these dams in the ways that beavers do. There is no way for humans to create a one and done solution for these restoration projects, there will always be a need for continuous construction on dam structures to be an effective form of stream restoration.

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