Dam Dimensions and Surface Porosity Affect the Water Storage Capacity of Beaver Dam Analogs Compared to Natural Beaver Dams

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Sawyer Nagle

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THESIS OF SAWYER NAGLE APPROVED BY

Date: 24 May 2024
Dr. Camille McNeely, Graduate Study Committee

Date: May 24, 2024
Dr. Rebecca Brown, Graduate Study Committee

Date: 24, May 2024
Dr. Brian Buchanan, Graduate Study Committee

Date: 05/24/24
Dr. Erin D. Dascher, Graduate Study Committee

ABSTRACT

Widespread stream incision in the Western United States, exacerbated by climate change and anthropogenic activities, necessitates effective restoration strategies. My study compares water retention by Beaver Dam Analogs (BDAs) to natural beaver dams and undammed control reaches. I compared how dam dimensions affect the hydraulic performance of both BDAs and beaver dams, revealing gaps in research on their comparative effectiveness. My study was conducted across eight watersheds in Washington state and two in Idaho. Hydraulic retention time (HRT), water travel time, and pool volume were response variables used to determine dam effectiveness. Dam height, thickness, length and porosity were the predictor variables. While BDA water travel times were significantly longer than control sites, natural beaver sites exhibited significantly higher HRT than BDA sites. Beaver dams were also significantly thicker and longer than BDAs. I identified dam thickness, height, and dam type as the most influential factors in determining HRT for both types. For BDAs, height and porosity significantly affected HRT, but among beaver dams, HRT had no significant predictors. Beaver dams also held a significantly larger volume of water than BDAs, with height and discharge as significant predictors. For BDAs, height alone significantly affected pool volume. Findings suggest that, while BDAs have a shorter water retention time compared to beaver dams, they do slow water compared to their control sites. My study highlights the need to consider dam

dimensions and surface porosity in the design of BDAs to enhance their effectiveness.

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INTRODUCTION

In recent years, the use of Beaver Dam Analogs (BDAs) as a restoration technique for mitigating stream incision has gained considerable attention among researchers and practitioners alike (Ciotti, 2021; Wheaton et al., 2019). BDAs, designed to mimic the functions of natural beaver dams, have shown promise in restoring degraded streams. However, despite the growing interest in their application, there remains limited research regarding the effectiveness of BDAs when compared to beaver dams (Lautz et al., 2018). Before delving into the potential of BDAs to repair incised streams, it is essential to first understand the underlying factors that contribute to stream incision.

Anthropogenic impacts such as grazing, agriculture, deforestation, wildfire, and beaver trapping can lead to the disconnection of streams from their floodplains, channel incision, and lowered water tables via processes such as mass wasting, surface erosion, and soil creep (Bylak & Kukula, 2022; Mikolajczyk & Nawrocki, 2019). In the western region of the United States, wildfire and historic agricultural practices are among the most significant contributors causing stream incision (Beechie et al. 2012, Rousseau & Pascal, 2009). In lowland valleys, agricultural methods like land clearing, overgrazing, and irrigation have left a legacy of destructive impacts on streams throughout the West, while climate change-caused mega-fires are exacerbating these impacts on their watersheds (Williams et al., 2019).

The warming effects of climate change have decreased precipitation and snowpack in the last several decades, creating prolonged drought conditions (Marlier et al., 2017). These drought conditions along with a history of fire suppression are increasing the frequency, duration, and severity of wildfire season across the Western United States (Williams et al., 2019; Westerling, 2016; Palmer et al., 2009; Schoennagel et al., 2017; Abatzoglou et al., 2017). When higher elevations that rely on snowmelt for sustained moisture experience warming temperatures, the timing of springtime snowmelt shifts to earlier in the year (Westerling, 2016). In the Pacific Northwest (PNW), this trend leads to less fuel moisture and earlier fire seasons that can last an average of eighty-four days longer than in past years (Westerling, 2016). Future climate projections based on models and historic trends predict frequency and impacts of mega-fires will continue to worsen in the Western U.S. (Halofsky et al., 2020). High-severity mega-fires carry such intense heat that they can sterilize the soil (Certini, 2005). These fires consume organic matter and can cause soil to become hydrophobic (Scott, 2000), creating a water-repellent soil layer that is less able to soak up water, reducing catchment retention and hydraulic conductivity (Gustine et al., 2022).

Erosion and Incision

A major consequence of mega-fires in watersheds is increased stream incision, resulting from short-duration, high-intensity rainfall onto landscapes with impermeable soil and a lack of vegetation (Shakesby & Doerr, 2006). Post-fire runoff can cause topsoil, rich in nutrients, as well as organic-laden ash and charred debris, to dislodge and erode into headwater channels (Wohl, 2020; Shakesby & Doerr, 2006). Once in the stream, the high velocity water can carry large volumes of topsoil and large woody debris, which can scour stream banks and incise stream bottoms (Beebe, 1997). Watersheds with steep gradients and abundant first-order streams are more likely to experience the highest degree of debris flow caused scour and incision (Kean et al., 2019; Shakesby & Doerr, 2006).

Across the Western US, deforestation and livestock grazing in riparian areas are also significant contributors to channel incision. Deforestation causes incision by removing vegetation cover that stabilizes stream banks, which can lead to increased erosion and sedimentation (Mikolajczyk & Nawrocki, 2019). Similarly, livestock grazing alters the vegetation structure through trampling and foraging (Fesenmeyer et al., 2018). These disturbances, if not properly managed, can result in degraded channels and unsuitable habitats for beavers (Small et al., 2016).

In this context, riparian vegetation plays a crucial role in stabilizing stream banks by utilizing its root system to bind the soil, prevent soil compaction, facilitate surface water infiltration, and reduce runoff (Abernethy & Rutherford, 2000).

However, deforestation and livestock grazing disrupt this natural process, leading to the loss of riparian vegetation and its associated benefits (Fesenmeyer et al., 2018). The absence of sufficient riparian vegetation further exacerbates channel incision, increases the risk of erosion and increased runoff during heavy rain events as well as elevating stream velocities (Abernethy & Rutherford, 2000).

Increased water velocity can lead to increased erosion and downstream flooding (Brooks, 1988). An incision that is deep enough will disconnect streams from their floodplains, alter water storage, lower groundwater tables, cause loss of wetlands and riparian areas, decrease summer base flow, and reduce populations of fish and invertebrates (Shields Jr. et al., 2010; Hardison et al. 2009; Shields et al., 1994; Tuckett & Koetsier, 2018). Streams suffering from incision can eventually recover to their original conditions, but it is a long-term, logarithmic process that can take hundreds to thousands of years (Wohl, 2017; Pollock et al., 2014).

Beaver Dams

Beavers, considered ecosystem engineers, are best known for three significant habitat alterations: cutting trees, building dams, and digging canals (Naiman et al., 1988). Beavers can play an active role in mitigating channel incision by manipulating water velocity. Beaver dams and their subsequent impoundments decrease water velocity by slowing and spreading water as it enters ponds (Naiman et al., 1988; Ecke et al., 2017; Gurnell, 1998). The slower water velocity increases long-term water retention, reduces peak flows, and can attenuate high-flow events by up to sixty percent (Puttock et al., 2021; Karran, 2018; Westbrook et al., 2020), ultimately extending the rainfall to peak discharge lag time (Puttock et al., 2017). Devito and Dillon (1993) noted an average HRT of 47 days within a beaver pond they studied. This slowing of the water velocity allows fine sediments and carbon-rich organic matter to settle out of the water column (Butler & Malanson, 1995; Puttock et al., 2017), reducing turbidity and sediment loads downstream (Bylak & Kukula, 2022). The sediment accumulating at the bottom of ponds can also hold substantial stocks of carbon (Naiman et al., 1994).

Beaver ponds can also influence stream habitat complexity by increasing the overbank flow that laterally connects streams to their floodplains, creating wetlands (Kivinen et al., 2020; Macfarlane et al., 2015; Burchsted et al., 2010). The overbank flow from flooding tends to deposit sediment rich with organic matter, leaf litter, and large woody debris into the wetlands, creating a significant long-term carbon sink (Laurel and Wohl, 2019). Beaver ponds, canals, and wetlands enhance landscape-scale surface water connectivity by establishing these lateral connections to floodplains (Puttock et al., 2017; Pollock et al., 2012). Impoundments created by beavers contribute to raised water table levels and aquifer recharge (Thompson et al., 2021; Westbrook et al., 2020). Beaver are also known to help mitigate the adverse effects of wildfire. Whipple (2019) found that streams with beaver have reduced phosphorous transport and pH post wildfire than streams without beaver and beaver activity has shown to increase the potential fire resistance of riparian zones (Weirich, 2021; Fairfax & Whittle, 2020).

Beavers were once abundant across North America, with estimated populations ranging from 60-400 million (or 3-10 beavers per stream km) before European settlement. However, the extensive trapping of beavers for their fur resulted in their near extinction in the early 1900s. By the 1930s, recovery efforts had begun as the ecological importance of beavers in stream systems became clear. Despite these efforts, by the late 1980s, only a fraction of the original beaver population, about 15 million, had been restored (Naiman, 1988).

In recent years, researchers and practitioners have shown a growing interest in beaver-related restoration strategies (Burchsted et al. 2010; Pollock et al., 2012; Macfarlane et al., 2015; Nash et al., 2021). These strategies range from discontinuing the trapping of beavers in stream systems with incised channels (Pollock et al., 2007) to manipulating sites to encourage beaver colonization (Macfarlane et al., 2015; Nash et al., 2021). However, it is worth noting that many streams are too incised and lack the habitat necessary to sustain beaver populations (Pilliod et at., 2018). To address this issue, many practitioners have shifted to installing man-made beaver dams known as Beaver Dam Analogs (BDAs) in streams that are too degraded to support beaver relocation (Macfarlane et al., 2015).

Beaver Dam Analogs (BDA)

Beaver Dam Analogs (BDAs), like beaver dams, are built to be semi-porous, channel-spanning, and are composed of similar materials. They ideally result in channel responses similar to natural beaver dams such as sediment retention, stream bottom aggradation, water storage and floodplain connectivity (Pollock et al., 2014; Bouwes, 2016). However, BDAs have emerged as a widely used tool despite limited research.

The few existing studies of BDAs have indicated various positive effects on thermal dynamics, biodiversity, fish passage, and sedimentation patterns (Charnley et al., 2018; Munir & Westbrook, 2021; Orr et al., 2020; Bouwes, 2016; Pilliod, 2018; Corline et al., 2022; Vanderhoof & Bert, 2018; Scamardo & Wohl, 2020; Pearce et al., 2021; Weber et al., 2017). However, these findings are not consistent across studies, nor do they all have desired outcomes. Munir and Westbrook (2021) found that BDAs increased stream temperature and a study by Pearce et al (2021) found no impact on stream temperatures at all. There are currently no studies that compare BDA water storage capabilities to beaver dams or quantify how much transient storage BDAs can generate (Lautz et al., 2018). Therefore, this study focuses on the influence that dam dimensions (including surface porosity) have on the impoundment volume and water storage capabilities of BDAs compared to beaver dams.

Comparing Natural Beaver Dams with Beaver Dam Analogs (BDAs)

Common BDA designs include starter dams, post-line-wicker-weaves (PLWW), and Constrictor dams (Bouwes et al., 2016; Scamardo & Wohl, 2020). Starter dams are the least porous and most similar to natural beaver dams. They are built by pounding vertical posts into the stream bottoms and then branches are woven between them. Fill materials like grass, gravel, and mud are then packed into the upstream side to retain water (Bouwes et al., 2016). PLWWs are built similarly to starter dams but without fill material. They rely on high-flow events and stream discharge to collect sediment and debris that eventually seal the dam (Bouwes et al., 2016). Constriction dams are the least like a beaver dam, they are primarily built to move sediment. One end of the dam is oriented downstream at an angle creating a hydraulic jet that targets erodible banks. The strategic placement of these “BDAs” can enhance stream sinuosity and promote natural sediment movement within the streams (Portugal et al. 2015).

Exploring BDA construction materials further, Orr et al. (2020) and Pearce et al. (2021) looked at the use of different weave materials. Since beaver favor willow, alder, and poplar for their dams (Pollock et al., 2014), they were curious about the suitability of alternative materials like dry upland conifers. Orr (2020) built five BDAs and wove three with juniper and two with willow. They found that both weave materials were equally effective at retaining flows.

Research has shown that packing either beaver dams or BDAs with mud and sediment can reconnect floodplains and elevate groundwater levels in adjacent riparian areas (Ronquist & Westbrook, 2021; Charnely et al., 2018; Pearce et al., 2021). Orr et al. (2020) reported that after using the juniper branches, roots mats, mud and cobble in their construction, there was a rise in groundwater levels of 18-30 cm up to 135 m upstream of BDAs and 12m into the adjacent floodplain. Similarly, Munir and Westbrook (2020) observed persistent ponding above BDA complexes built with aspen branches and sealed with mud.

Studies that examine the efficacy of BDAs, and/or beaver dams, based on their dimensions remain scarce. Most studies that have looked at beaver dams often only focus on descriptive statistics such as mean, maximum, and minimum values of their dimensions, but do not use these measurements to analyze the landscape (Woo & Waddington, 1990; Morgan, 1868, Dugmore, 1914, Townsend, 1953, Butler, 1995). However, there was a paper from 2017 that used aerial imagery and dam dimensions to estimate pond volume. They determined that beaver pond volume correlated with dam height, length and pond area (Karran et al. 2017). Hafen et al. (2020) looked at height as a response variable of stream discharge, drainage area, slope and dam type (primary and secondary). They found that all these variables predicted dam height, but that type was the most significant predictor. They also noted that one meter was the average height out of the 500 dams that they measured. In her master's thesis, Cavin (2015) compared the dimensions of beaver dams between two sites and observed no significant differences in dam dimensions. Woo and Waddington (1990) took a different approach and classified dams based on their materials, preservation stage, and flow types. They also noted that the ability of a dam to hold water is directly related to the amount of sediment packed into its pore spaces. Ronnquest and Westbrook (2021) built upon the work of Woo and Waddington (1990), by introducing two more flow types. They also investigated the relationship between beaver dam dimensions, construction materials and flow types. They discovered that beaver dam material correlated with both dam height and length, with wood-based dams being both significantly shorter in length and taller than those made of sediment (Ronnquist & Westbrook, 2021). Though I was unable to find any studies that directly looked at the porosity of dams, Gurnell (1998, pg. 179) wrote that "the volume of water stored is also a function of the degree to which the beaver dam is watertight." The only study I found on BDA dimension was by Scamardo and Wohl (2020). They found that the amount of sediment stored above BDAs was positively correlated with dam height and the impoundment surface area. I could not find any studies that directly compared BDAs to beaver dams.

To address this knowledge gap, my study compares ten BDA complexes, constructed by five different organizations across ten streams within six watersheds in Washington, to eight beaver dam sites found across both Washington State and Idaho. By analyzing variations in construction, specifically the differences in dam dimensions and surface porosity, I will contribute to a growing body of literature showing how these variables influence the ability of BDAs to hold and store water. Insights from my analysis could help guide the design of BDAs in future stream restoration efforts. Emphasizing the role of thickness, height, length and porosity in BDA design may provide a more nuanced perspective on how these artificial structures can best mimic natural beaver dams.

Study Objectives

1. Determine whether BDAs effectively slow water by comparing them to unrestored and paired control reaches.
2. Examine the role of porosity in determining water storage capacity and hydraulic residence time for BDAs.
3. Compare the dimensions of BDAs, including thickness, height, area, and length, to beaver dams.
4. Evaluate how specific construction characteristics, thickness, height, length, area, and porosity influence pond volume and hydraulic residence time for BDAs.

5. Evaluate how specific construction characteristics, thickness, height, area and length influence pond volume and hydraulic residence time for beaver dams

Hypothesis

I hypothesize that BDAs will have slower water travel times than their paired control reaches which will indicate enhanced water retention. I predict that the physical dimensions (thickness, height, area and length) of BDAs and beaver dams will significantly determine their hydraulic residence time and pool volume, with larger dimensions associated with greater water storage. Furthermore, I expect that surface porosity will inversely affect the water storage capacity of BDAs. Additionally, I anticipate that there will be significant differences in these dimensions between beaver dams and BDAs. Finally, I anticipate that beaver dams will have longer hydraulic residence times and larger pool volumes compared to BDAs.

METHODS

Study Area and Site Selection

The study areas for my project are within eight Washington state watersheds and two Idaho watersheds. Four are located in Eastern Washington (Hangman, Little

Spokane, Spokane, and Crab Creek), four are located in North Central Washington (Entiat, Okanogan, Methow, and Wenatchee), and two are located in North Idaho (Palouse and Clearwater) **(Fig 1, Table 1, Table 2)**. The specific locations of the beaver sites have been kept confidential to ensure the protection of the beaver communities. For reference, I have assigned the sites a naming system, denoting them with numbers: 1-8.

The selection of restoration sites was based on the timing of BDA construction, which took place between 2018 and 2022 **(Table 1)**. Matched control sites were found upstream of the BDA sites and were chosen for their similarities in both elevation and discharge. Two sites, Potato and Rattlers Run, did not have control reaches. Potato Creek was an intermittent stream, and I could not find a reach that had a similar discharge to the BDA reach. Both the upstream and downstream reaches for the Rattlers Run site were on private property and inaccessible. Many potential beaver complex sites were scouted, but only eight were identified as reasonable matches **(Table 2)**. Beaver sites were considered reasonable matches if they existed in smaller stream channels, found at similar elevations as the BDAs, had similar discharge rates as BDA sites, and had dams less than 25 meters long**.**

Three of the restoration sites and four beaver sites are located in the Methow and Okanogan watersheds (Texas, Cow, Chiliwist, 1, 2, 3 and 4). These watersheds are situated along the eastern foothills of the North Cascades and due to their location, are directly exposed to the rain shadow effect. This means that these watersheds are more vulnerable to water scarcity and drought conditions. In the summer of 2014, the lightning-caused Carlton Complex Fire burned an area of over 103,644 ha between these two watersheds. In August of that same year, massive downpours created catastrophic flood events within the region (Kershner, 2014).

To provide context on the water availability in the Methow and Okanogan watersheds, data from the National Climatic Data Center (NCDC) indicates that Okanogan County, where both watersheds are located, has an average annual precipitation of 57.4 cm (NOAA, 2024). This precipitation is predominantly in the form of snowfall, with the majority occurring from November to March. The combination of lower precipitation levels, the record breaking 2021 drought and the significant impacts of the Carlton Complex Fire in 2014, the Okanogan Complex Fire in 2015, and the Walker Creek Fire in 2021 have contributed to the stream degradation within the Methow and Okanogan watersheds (Norris, 2022).

Three other restoration sites and two beaver sites are found in the Entiat and Wenatchee watersheds (Potato, Roaring, Alder, 5, and 6). All are found on the east slopes of the Cascade Mountains in north central Washington. The higher elevations in the northwest portion of the Entiat Watershed receive about 90 inches of precipitation annually, most of which occurs as snow (CCCD, 1999). The lowest elevations, near the town of Entiat, receive about IO inches of precipitation (CCCD, 1999; Berg & Mathews, 2002). The Wenatchee Watershed originates in high mountainous regions of the Cascade Mountains, with numerous tributaries draining subalpine regions within the Alpine Lakes and Glacier Peak Wilderness areas. The dominant climatic factors shaping the watershed primarily result from the Cascade Mountains and the prevailing westerly winds. The rainshadow effect, associated with moist air originating from the Pacific Ocean, comes into play as this air encounters the Cascade Mountains. Consequently, this can lead to increased amounts of precipitation on the windward side of the mountains, resulting in heavy annual rainfall of nearly 150 inches and snow accumulations exceeding 25 feet at the mountain's peak (Berg & Lowman, 2002). During the winter months, daily temperatures in the rain shadow region, on the leeward side of the mountain, range from an average of 25°F to 40°F (Fahrenheit), while the summer months typically see temperatures ranging from 60°F to 80°F (Andonaegui, 2001). As these air masses continue eastward towards the Columbia Basin, the rain shadow effect progressively diminishes moisture, creating an arid environment in the lowermost section of the watershed (Andonaegui, 2001).

The last four restoration sites and two beaver sites are located along the Washington-Idaho border (Thompson, Ratters Run, Deadman and Crab, 7 and 8). The Little Spokane, Spokane, Hangman, and Crab watersheds are located in eastern

Washington. They are situated to the west of the Selkirk Mountains in Spokane and Thurston counties. These watersheds receive an average annual precipitation of 50.8 cm, with approximately two-thirds of the precipitation occurring as snowfall (NOAA, 2024). The Idaho sites are located in the Palouse and Clearwater watersheds east of Moscow, Idaho.

Study Design

I conducted a comparative measurements design that compares ten treatment reaches with Beaver Dam Analogs (BDAs) to eight incised control reaches, along with eight reference reaches containing beaver dams. All of the BDAs were built using a similar standardized method, each of them had between one and three rows of pounded posts and all were then woven with either conifer or hardwood branches. A few sets of dams were further reinforced with sediment and cobble (Potato, Roaring and Alder). Variations were noted in thickness, length, area, height and porosity among the different sets of BDAs.

Measurements for all sites were conducted throughout the summer of 2023 (July-September). I collected hydrology data during the summer because there is minimal rainfall and runoff and a relatively stable streamflow. With less influence from external flow inputs this isolated the dams' effects and provided a clearer picture of the water retention capacity. For all dam sites, watershed area and stream order were calculated using 30-meter Digital Elevation Models (DEMS) from USGS Earth Explorer and a 10 digit watershed boundary dataset in HUC8 from USGS Geodata Spatial Gateway as well as the hydrology toolset in ArcGIS Pro version 3.2.2 (U.S. Geological Survey, 2014; U.S. Department of Agriculture, Natural Resources Conservation Service, 2013; Esri, 2023).

Specific BDA Study Sites:

Rattlers Run Creek-WRIA 56 (Hangman Watershed)

Rattlers Run Creek is a small tributary within the Hangman Watershed. It is located Southwest of Spokane, Washington and drains the Blossom Mountain headwaters in Idaho. The watershed includes 174,015 ha of drainage area, 86,187 ha of agriculture, and 357 km of perennial streams (Wa.gov, SpokaneWatershed.org). Rattlers Run Creek had two phases of BDA installation, in 2019 three BDAs were built and then eight more were added in 2022 (**Table 1**).

Thompson Creek-WRIA 57 (Spokane Watershed).

Located within the Spokane River Watershed, Thompson Creek runs from the southern slopes of the Selkirk Mountains, through agricultural lowlands, into Newman Lake. Historical agricultural dredging has caused downstream sedimentation, with sediment-bound phosphorus emerging as a primary contributor to heightened lake eutrophication. In order to mitigate the sedimentation eighteen BDAs were installed throughout the fall of 2022 (**Table 1**).

Deadman Creek-WRIA 55 (Little Spokane Watershed)

Deadman Creek was historically a major stream draining a 426 km^2 basin below Mt. Spokane. Located within the Little Spokane Watershed in Northeastern Washington, the land use varies from pristine forests, rangeland, and agriculture to expansive urban development (Washington Dept of Ecology 1995). Five BDAs were installed in the fall of 2022 (**Table 1**).

Texas Creek-WRIA 48 (Methow Watershed)

Texas Creek is a tributary of the Methow River Watershed in North Central Washington, draining 4665 km^2 of stream. The north fork of Texas Creek runs down Mt. Leecher and the segment of the North Fork of Texas Creek receiving stream flow restoration actions is on Washington Department of Natural Resource (WDNR) lands. This creek has experienced the legacy impacts from beaver removal, timber harvest, road building, agricultural irrigation, abstraction, livestock use, as well as severe wildfire and subsequent precipitation induced debris flows. It currently experiences active livestock grazing on the site every summer (Whipple 2021). In May of 2022 thirty-three BDAs were installed along Texas Creek, eight of them are located within our 200m study reach. Construction materials consisted of two rows of three inch diameter posts woven with ponderosa pine (*Pinus ponderosa* (**Table 1**)).

Cow Creek-WRIA 48 (Methow Watershed)

The segment of Cow Creek that received restoration is on a combination of WDNR and private lands and has experienced the legacy impacts of beaver removal, timber harvest, road building, agricultural irrigation abstraction, livestock use, as well as severe wildfire and subsequent precipitation induced debris flows (Whipple, 2021). In November of 2022, thirty-three BDAs were installed. Construction materials consisted of two rows of three-inch in diameter posts woven with ponderosa pine (*Pinus ponderosa* (**Table 1**)).

Chiliwist Creek-WRIA 49 (Okanogan Watershed)

Chiliwist Creek is a tributary within the southern part of the Okanogan RIver Watershed. It runs down the north side of Dent Mountain and into the Chiliwist Valley, and then east into the Okanogan River. The segment of Chiliwist Creek that received restoration is on private lands and has experienced the legacy impacts of beaver removal, road building, agricultural irrigation abstraction, livestock use, as well as severe wildfire and subsequent precipitation induced debris flows (Whipple, 2021). In July of 2022, thirty-one BDAs were installed in this creek, twenty are located within our 200m treatment reach. Construction materials consisted of two rows of three-inch diameter posts woven with ponderosa pine (*Pinus ponderosa*) (**Table 1**).

Crab Creek-WRIA 43 (Upper Crab-Wilson Watershed)

The headwaters of Crab Creek are located just north of HWY 2, runs down Getty's Butte. Named for its abundance of crayfish, it is 163 miles long and drains a 13,200 km^2 watershed. Carved by the ancient floods of Lake Missoula, it is sometimes referred to as the "longest ephemeral stream in North America" (KWA Ecological Sciences Inc., 2004). The segment of Crab Creek receiving restoration is on private land and has experienced a century of livestock use, channelization and tillage for wheat production (KWA Ecological Sciences Inc., 2004). Twenty-five BDAs were installed during the Fall of 2018 and Spring of 2019 (**Table 1**).

Alder Creek-WRIA 45 (Wenatchee Watershed)

Alder Creek is located on the east side of the Cascade Mountains in the Wenatchee National Forest. The creek runs through the Entiat Mountain Range into the Chiwawa River. In August of 2022, a restoration reach, located next to a horse camp, was installed to help create more fish habitat (**Table 1**).

Potato Creek-WRIA 46 (Entiat Watershed)

Potato Creek is a tributary of the Entiat River located on the east side of the Cascade Mountain Range. Its watershed drains the SW side of Baldy Mountain. The segment of Potato Creek that received restoration is on Forest Service Land. Phase 1 of the structures were installed in the fall of 2020 after experiencing the key legacy impacts of beaver removal, timber harvest, road building, as well as severe wildfire and subsequent precipitation induced debris flows. Phase 2 of installation was in the summer of 2022 (**Table 1**).

Roaring Creek-WRIA 46 (Entiat Watershed)

Roaring Creek is a tributary of the Entiat River located on the east side of the Cascade Mountain Range in the Wenatchee National Forest. The Roaring Creek Watershed drains the SE side of the Entiat Ridge into the Entiat River. Structures were built in 2020 in order to create fish passage due to head cutting in the stream (**Table 1**).

Porosity

Porosity refers to the amount of void space or empty volume within a material or substance. It is a measure of how much of the total volume is occupied by pores or open spaces compared to the solid material (Hook, 2003). Porosity is typically expressed as a percentage or a fraction, representing the ratio of the pore volume to the total volume of the material.

I measured porosity using an area fraction approach on high-resolution images. The high-quality images (<10cm resolution) were captured using an

Olympus OM-D E-M10 Mark IIIS camera during early morning hours to minimize shadows. For consistency, I used specific camera settings (autofocus and 14mm).

Because there were anywhere between 60-500 images per dam, I created a subsampling protocol that used an online random number generator to choose 60 images from each dam to analyze (Calculator.net, 2008). The images were then processed using ImageJ 1.54 g software (Schneider et al., 2012). The RBG images were converted to 16-bit in order to catch any subtle intensity variations in the images. The images were then segmented using intensity thresholding. Segmenting is a process that delineates pixels into regions of interest (ROI). Intensity thresholding does this by labeling each pixel by its intensity value. Intensity is a measure of brightness. Thresholding then segments the dam structure materials from the background, essentially defining the region of interest for analysis (Mateos-Perez & Pascau, 2013).

I then configured the measurements to include "Area" and "Area Fraction". This analysis shows both the total area of the dam and the percentage area occupied by the dam materials. Using the "Measure" command under the "Analyze" menu, I then computed the area and area fraction for the selected regions. The results provide a percentage of the image area covered by the dam. This gives the percentage of wood, sediment, rock and vegetation compared to the whole image. I inverted that number to find the percent porosity. I then averaged the percent porosity of all the images taken of a dam to create an overall percent porosity for each dam.

I was only able to measure the porosity of the BDAs due to the upstream water-holding side of beaver dams being 99% underwater and therefore inaccessible. The downstream sides of beaver dams generally do not have the sediment-packing that is typically present on the upstream side. This indicates that the downstream sides of the beaver dams are unlikely representative of their water-holding capacity, thus I did not measure the downstream side of the dams. BDAs tended to be more homogenous in their structure, so I measured the porosity of both sides of each BDA. As only the outer layers of the BDAs can be measured, I made an assumption of homogeneity throughout the dams.

Hydraulic Conductivity

To determine the Hydraulic Conductivity of the beaver dams I used Darcy's Law ($Q=-KA(\Delta h/\Delta L)$ (Woo & Waddington, 1990). Darcy's Law is an equation used to calculate the flow rate (Q) through a porous medium based on the hydraulic conductivity (K), cross-sectional area (A), and the hydraulic gradient (change in hydraulic head (h) over the length of the flow path ($\Delta h/\Delta L$)). The negative sign for hydraulic conductivity indicates that flow occurs in the direction of decreasing hydraulic head.

Darcy’s law assumes a laminar flow pattern through the dams. To determine turbulent, transitional, or laminar flow the Reynolds numbers (Re) were calculated for each dam ($Re=(pvD)/u$), where p is fluid density, D is the diameter of dam pore space, V is fluid velocity, and u is dynamic viscosity of fluid. Most beaver dams had low enough Re (<2000), indicating a laminar flow through the dams, whereas the BDA flow patterns were >2000 and therefore hydraulic conductivity could not be measured for BDAs (Kennedy, 2023).

Water Retention

To compare the water retention capabilities between BDAs and beaver dams, I measured the average Hydraulic Retention Time (HRT) for each dam within a five-impoundment complex. HRT represents the average time that water remains within the impoundments before being released downstream. It was calculated using the equation HRT = V / Q, where V is the volume of water stored in the impoundments and Q is the discharge or flow rate of water entering the impoundments (Danckwerts, 1995). Pool volume was measured using a transect method and multiple depth measurements. Ten equally spaced transects were measured down the length of a pond and then ten equally spaced depth measurements were recorded along each transect. Discharge was estimated using the cross-sectional area method using a Hach FH950 flow meter (Gordon et al., 2004). By dividing the total volume of water stored in the impoundments by the flow rate, the HRT provided an estimate of the average residence time of water within the impoundment. This parameter helps to understand the water storage dynamics within the reach (Karran et al., 2017).

To test whether BDAs were slowing water, I measured water travel time (WTT) for each BDA reach and its paired control reach. Travel time is defined as the mean time it takes for a particle of water to travel from the upstream end of a reach to the downstream end (Gordon et al., 2004; Jin et al., 2007). I conducted conservative tracer injections in each treatment reach to investigate WTT using either sodium chloride or rhodamine. For these measurements, an injection reach was selected within each of the 10 study sites to include at least five impoundments. The injection reach length varied between sites and was later normalized to 200 meters.

A fluid metering International pump was positioned approximately 15 meters above the upstream end of each injection reach to regulate the drip rate. Conductivity or rhodamine measurements were then employed to monitor the movement of the tracer drip at both the upstream and downstream locations of the study site. I used a handheld YSI 556 Multimeter to measure conductivity once per minute at each location (Gordon et al., 2004; Jin et al., 2007). For rhodamine, I used Turner Aquafluor handheld fluorometers. Subsequently, I recorded the observed changes in tracer concentration, including the increase, plateau, and decrease, at both locations. WTT was assessed by comparing the time it takes for the tracer to reach plateau concentrations at the upstream end of the reach with the corresponding time at the downstream end (Stream Solute Workshop, 1990).

I opted not to measure WTT for beaver reaches due to the distinct hydraulic characteristics of these environments. Beaver dams create impoundments that significantly slow water movement, resulting in prolonged water residence times within these reaches. WTT measurements that use tracer injections to assess flow dynamics can lead to extended travel times spanning days or longer. Instead, I measured HRT because it provided a more comprehensive assessment of water storage dynamics within beaver impoundments by considering factors such as volume of water stored and flow rate.

Dam Characteristics and Dimensions

To investigate the roles that different construction dimensions of dams play in water retention, I collected multiple measurements of both BDA and beaver dams (**Tables 4, 5, 6**). For each dam, I determined the average thickness by taking five measurements along the length. The length of each dam was also measured. Additionally, for each dam I calculated the dam height by measuring the highest point on the dam crest to the lowest point on the streambed downstream of each dam (Hafen et al., 2020). The area of each BDA was calculated using the formula for the area of a rectangle (thickness multiplied by height), while the area of the beaver dams was determined using the formula for the area of a triangle (height multiplied by thickness divided by 2).

Data Analysis

Travel Time

Water travel times were normalized across all sites to a 200 m stretch of stream. To determine if BDA sites had greater WTTs than their paired control sites, I used a paired t-test. Two of the BDA sites (Potato and Rattlers Run) did not have a control reach and therefore were not included in the travel time measurements. This model was then visualized in RStudio using ggplot2 package (RStudio, 2023).

Impoundment Volume and Hydraulic Residence Time

To compare the HRT and the volume of water in the impoundments between beaver and BDA ponds, I first log-transformed the data to address issues with normality and improve data distribution. I then conducted Welch Two-Sample t-tests. To determine if there were significant differences between sites, I first ran ANOVAs of HRT by site and Volume by site and then applied Tukey's Honestly Significant Difference (HSD) test to identify which sites were significantly different from each other. The models were then visualized using the ggplot package (RStudio, 2023).

To understand which predictor variables (Height, Length, Thickness, Discharge, Porosity and Permeability) predict HRT or impoundment volume, I first used the MuMIn package in RStudio (version 2023) to run a dredge plot. The dredge plot explores multiple models with different combinations of predictor variables while controlling for the effect of the other response variable. Once the best model was determined, I ran a Type 2 ANOVA to assess the significance of the predictor variables on volume and a Type 3 ANOVA to assess the significance of the predictor variables on HRT. These models were then visualized using the ggplot2 package (RStudio, 2023).

Porosity

To compare the porosity across BDA sites, I first log-transformed the data to address issues with normality and improve data distribution. To determine if porosity was a significant predictor of either pool volume or HRT, I made a subset of the data that only included BDA type and ran multiple linear regression models that included porosity. This model was then visualized using the ggplot2 package (RStudio, 2023).

Hydraulic Conductivity (Permeability)

To compare the hydraulic conductivity across beaver dam sites, I first log-transformed the data to address issues with normality and improve data distribution. To determine if hydraulic conductivity was a significant predictor of pool volume or HRT I made a subset of the data that only included beaver dams and ran multiple linear regression models that included permeability. I then visualized this model using the ggplot2 package (RStudio, 2023).

Principal Component Analysis (PCA)

To visualize the multidimensional structure of the dataset and identify patterns related to structural dimensions and water storage characteristics between beaver dam analogs and natural beaver dams, I created multiple Principal Component Analysis (PCA). The PCAs were then implemented using the 'ggord’ and ‘vegan’ packages in Rstudio, and the first two principal components were retained for visualization purposes. Scatter plots were generated to display the distribution of dams in the reduced-dimensional space. These help to provide insight into the relationships between dams, dam types and dam dimensions.

RESULTS

Travel Time

Water traveled about twice as slowly through BDA reaches compared to paired control reaches (paired t-test, t= 2.999, df =7, $p<0.05$, **Fig 2, Table 3**). BDA and control reaches had mean water travel times of 44.3 and 23.6 minutes per 200 m, respectively. BDA sites had significantly longer travel times than their control. Chiliwist Creek had the shortest time difference between its BDA and control reach at 4 minutes, while Thompson Creek had the longest time difference between BDA and Control at 73.5 minutes (**Table 3**).

Impoundment Volume

Beaver impoundment pool volumes were, on average, much larger than those created by BDAs. BDA and Beaver sites had mean pool volumes of 7,810 and 162,000 liters respectively (**Table 4**). Beaver sites had significantly higher pool volumes than the BDA sites (Welch Two Sample t-test, t= -9.504, df = 65.4, $p=<0.0001$, **Figs 9 & 10**). Crab Creek BDA reach had the highest average pool volume for all BDA sites (14,000 liters), and Potato Creek had the lowest average BDA pool volume (40 liters) (**Table 4**).

When including both beaver dams and BDAs in the analysis, dam height and type significantly predicted pool volume (R^2=0.67, F(3, 66)=47.38, p<0.0001, **Fig 10**). Among only BDAs, height emerged as a significant predictor of pool volume, with thickness showing marginal significance (R^2=0.375, F(3, 29)=7.405, p<0.001, **Fig 10**). Among only beaver dams, height and discharge were significant predictors of pool volume (R^2=0.247, F(4, 22)=3.14, p<0.05, **Fig 10 & 11**).

Hydraulic Residence Time

BDA and Beaver impoundments had mean HRTs of 0.13 and 71 hours respectively (**Table 4**). For BDA impoundments, Rattlers Run Creek had the longest average residence time of 0.85 hrs and Chiliwist Creek had the shortest residence time of 0.007 hrs (**Table 5**). For Beaver impoundments, site number 7 had the longest average residence time of 407 hrs and site 4 had the shortest with 0.4hrs (**Table 6**). Beaver impoundments had significantly higher residence times than the BDA sites (Welch Two Sample t-test, t=-3.72, df = 48, p=0.0001, **Fig 3 and Fig 4**).

Of the dam construction predictor variables (thickness, height, length and type), height, thickness, and type had the strongest correlation with HRTs, as indicated by a significant model fit (R^2=0.71, F(3, 66)=57.5, p<0.0001, **Fig 5, Fig 6, Table 7**). Among only BDAs, height and porosity were the significant predictors of

HRT (R^2=0.58, F(2,30)=23.09, p<0.0001, **Fig 5, Fig 7**). Among only beaver sites, there were no significant predictors of HRT.

Dam Construction Variables

Beaver dams were significantly thicker than BDAs (Welch Two Sample t-test, t=-3.72, df = 33.7, p<0.001, **Fig 15**). For BDAs, the lowest average thickness was 36.3 cm and thickest dams on average were 111 cm (**Table 4**). For Beaver dams, the lowest average thickness was 82 cm and the thickest dams on average were 206 cm (**Table 5**). Beaver dams were significantly longer than BDAs (Welch Two Sample t-test, t= -1.06, df = 54.8, p<0.05, **Fig 15**). For BDAs, the shortest dams were on average 209 cm and the longest dams on average were 2,320 cm (**Table 4**). For beaver sites, the shortest dams were on average 451 cm and the longest dams were on average 1,150 cm (**Table 5**). There was no significant difference in mean dam area between types (Welch Two Sample t-test, t= 1.81, df = 49.2, p = 0.075, **Fig 15**). There was also no significant difference in mean height between types (Welch Two Sample t-test, t= 1.42, df = 66.4, p=0.16, **Fig 15)**.

PCA for all Variables and Complete Data Set (**Fig 16, 17, 18**)

The first Principal Component Analysis (PCA) biplot shows the patterns between BDA and beaver dams. They are visualized based on multiple log-transformed structural measurements and the response variables volume and HRT (**Fig 16**). PC1 and PC2 together capture 68.85% of the variability within the dataset, with PC1 being the dominant axis explaining 40.89% of the variance. The vectors representing volume, area, thickness, HRT and height are closely clustered and directed towards the positive side of PC1, indicating a strong positive relationship among these variables and their collective influence on this principal component. These structural variables, being closely related, suggest that larger pool volume as well as longer residence time in dam impoundments is associated with greater dam area, thickness, and height. The stream discharge and dam length predictors are pointing towards the negative side of PC2 and the positive side of PC1, indicating a divergent relationship with the other variables. Observations (dams) are clustered by group, with BDA dams represented in red and beaver dams in blue. The spatial separation of these groups on the biplot indicates differences in their characteristics, as captured by the PCA. This differentiation is linked to variations in their structure and hydrologic responses, as influenced by the predictor variables. Overall, the PCA suggests that while BDA and beaver dams share some structural similarities, there are distinct differences.

The second PCA biplot shows the patterns among BDA sites. These are also visualized based on multiple log-transformed structural measurements and the response variables Volume and HRT (**Fig 17**). PC1 and PC2 together capture 73.72% of the variability within the dataset, with PC1 being the dominant axis explaining 46.79% of the variance. The vectors representing volume, area, thickness, HRT and height are again closely clustered and directed towards the positive side of PC1, indicating a strong positive correlation among these variables and their collective influence on this principal component.

The last PCA biplot shows the patterns among Beaver sites. These are also visualized based on multiple log-transformed structural measurements and the response variables volume and HRT (**Fig 18**). PC1 and PC2 together capture 74.44% of the variability within the dataset, with PC1 being the dominant axis explaining 50.99% of the variance. The vectors representing volume, area, thickness, HRT and height are again closely clustered and directed towards the positive side of PC1, indicating a strong positive relationship among these variables and their collective influence on this principal component.

DISCUSSION

Despite the growing application of BDAs, our understanding of their ability to slow and store water relative to beaver dams has remained limited (Ciotti, 2021; Wheaton et al., 2019). My study contributes to the existing research on stream restoration techniques by offering new insights into the water storage capabilities of BDAs compared to beaver dams. This is important as we face escalating environmental challenges like climate change, severe wildfire, and wildfire-induced incision.

My study is among the first to quantitatively compare how well BDAs slow and store water. My first goal was to understand whether BDAs could slow and store water compared to their undammed control reaches. My second goal was to see if they could do it as effectively as beaver dams and my third goal was to see what dimensional characteristics predict these abilities. My study provides evidence that that BDAs do indeed slow and store water when compared to undammed control reaches. However, they have both shorter hydraulic residence times and lower pool volumes compared to beaver dams. Dam characteristics such as height, thickness, and porosity significantly affect how well dams slow and store water.

As I expected, BDAs effectively doubled the water travel time in the restoration reaches compared to their unrestored control reaches. This slowing of water increases their potential to reduce erosion, promote sediment deposition, stabilize stream banks, and promote nutrient retention (Bylak & Kukula, 2022; Ensign & Doyle, 2005). Furthermore, their ability to moderate water flow during summer low flow conditions means that BDAs could also have the potential to help with flood mitigation during high flow events (Karran, 2018; Puttock et al., 2021).

My investigation of impoundment volume and HRT supported my hypothesis that beaver dams significantly accumulate and store more water than BDAs, with a mean pool volume difference of approximately 2000% and a mean HRT difference of 200%. The high pool volume and hydraulic residence in beaver impoundments is not surprising and is well documented (Devito & Dillon, 1993; Puttock et al., 2021; Karran, 2018; Westbrook et al., 2020). BDAs, however, on average held water less than an hour but showed a considerable range in the sizes of their impoundments, from as little as 40 liters to as much as 51,400 liters.

I also found that dam height was one of the most important factors in predicting both pool volume and HRT for the combined BDA and beaver dam dataset, suggesting that taller dams have a greater capacity to collect and store water. However, for hydraulic residence times of both Beaver dams and BDAs collectively, I found that along with dam height, thickness also significantly influenced water retention capabilities. This means that thicker and taller dams will slow and store more water than thin and short dams.

In both the BDA subset and the beaver dam subset, height was again found to be a predictor of pond volume, which is consistent with the findings of Karran et al. (2017). However, unlike their study, length did not also predict pond volume. Despite the similar heights between BDAs and beaver dams, we can attribute the significance of dam height as a predictor of pond volume in both types to the fact that a taller dam height will increase the volume capacity of the dams, directly impacting the residence time of water within the impoundment.

However, for beaver dams, discharge also predicted beaver pond volume, indicating that the rate of water flow directly impacts the amount of water there is available for a beaver dam to retain. The absence of discharge as a significant predictor, as well as an R^2 value of 0.38, for BDA pond volume suggests that other variables, possibly related to construction techniques, materials used, or local topographic conditions, play a more important role in determining their impoundment capacity.

For the combined dataset, the role of thickness as a significant predictor of hydraulic residence time presents an interesting picture when comparing BDAs to beaver dams. The beaver dams were generally about twice as thick as the BDAs. The mean thickness for beaver dams was ~ 1.25m which is supported by Butlers (1995) findings that most beaver dams are built between 1-2 m wide. Dam thickness likely contributed to their higher water retention and extended HRTs. The thicker the dam, the increased capacity for water storage.

When analyzing BDA and beaver dam subsets independently, the predictive value of thickness significantly diminished. This shift can likely be attributed to the standardized construction practices prevalent in BDA projects. BDAs are built to mimic the ecological functions of beaver dams but do not fully replicate the degree of thickness observed in natural dams. BDAs tend to be built with distinct objectives in mind, such as habitat enhancement, sediment trapping, and peak flow reduction, leading to a standardization of construction parameters including thickness (Bouwes, 2016). The minimal variability in dam thickness across BDAs can reduce its influence on HRT when compared to other variables like surface porosity. Consequently, it becomes evident that certain variables, specifically porosity and dam height, emerged as more important in determining the hydraulic residence time for BDAs.

Permeability is determined in part by the porosity and pore connectivity of a structure; the more interconnected the pores, the easier it is for water to pass through. This directly affects the retention time of water within dam impoundments. Beaver dams, for instance, are often densely packed with mud and sediment to decrease permeability and minimize water flow. However, BDA builders often face challenges in replicating this aspect of dam construction. Obtaining the necessary permits to add or move sediment within streams can be an obstacle. Without the addition of sediment to reduce permeability, the potential water holding capacity of BDAs will remain low.

For beaver dams, the absence of significant predictors for hydraulic residence time shows how dynamic these structures are. Beaver dams are not the product of a standardized design but are instead tailored by the beavers themselves to their specific environments. They are consistently responding to the ongoing changes in stream water flow and sediment deposition. Beaver are so efficient at building their dams it generally results in the upstream, water-holding side of the dam being fully submerged (Gurnell,1998). Observation and the beavers' known behavior of integrating sediment into their dams suggests that beaver dams would likely exhibit lower porosity compared to BDAs. However, even though it is likely that porosity would have been a predictor for beaver dams, the inability to directly measure this variable limits our understanding and necessitates further exploration.

Future directions for research could explore topography as a predictor of pool volume as well as exploring more methods of determining porosity of beaver dams (for example, remote sensing techniques). Using a BACI design to observe water holding capacity over time, as well as experiments that compare different dam designs in a variety of stream attribute types (for example, sediment loads and discharge rates), could systematically assess which dam designs are most effective in each stream type. Also, given how well beaver ponds are known to sequester carbon, it would also be beneficial to assess how well BDAs are able to sequester carbon in comparison to beaver dams (Wohl, 2013).

In conclusion, while BDA impoundments exhibit shorter residence times than their beaver counterparts, their capability to substantially slow water flow relative to unrestored sites demonstrates their potential in mimicking the beneficial effects of beaver dams. In arid climates increased water storage will be important as reduced snowpack, droughts, and wildfires are increasing (Westerling 2016). These findings support my initial hypothesis that the dimensions and surface porosity of these structures play an important role in their ability to retain water and regulate flow. Considering these insights, I suggest maximizing dam height and thickness, and minimizing surface porosity in BDA construction. This approach could entail adding extra rows of posts and weave to bolster dam thickness for longer water retention, as well as increasing the height of the dams in order to capture more water. I also encourage the use of stream sediment in reducing the porosity of the dams when water storage is a primary goal of the BDAs. This is especially important in sediment-starved or low-discharge streams

FIGURES

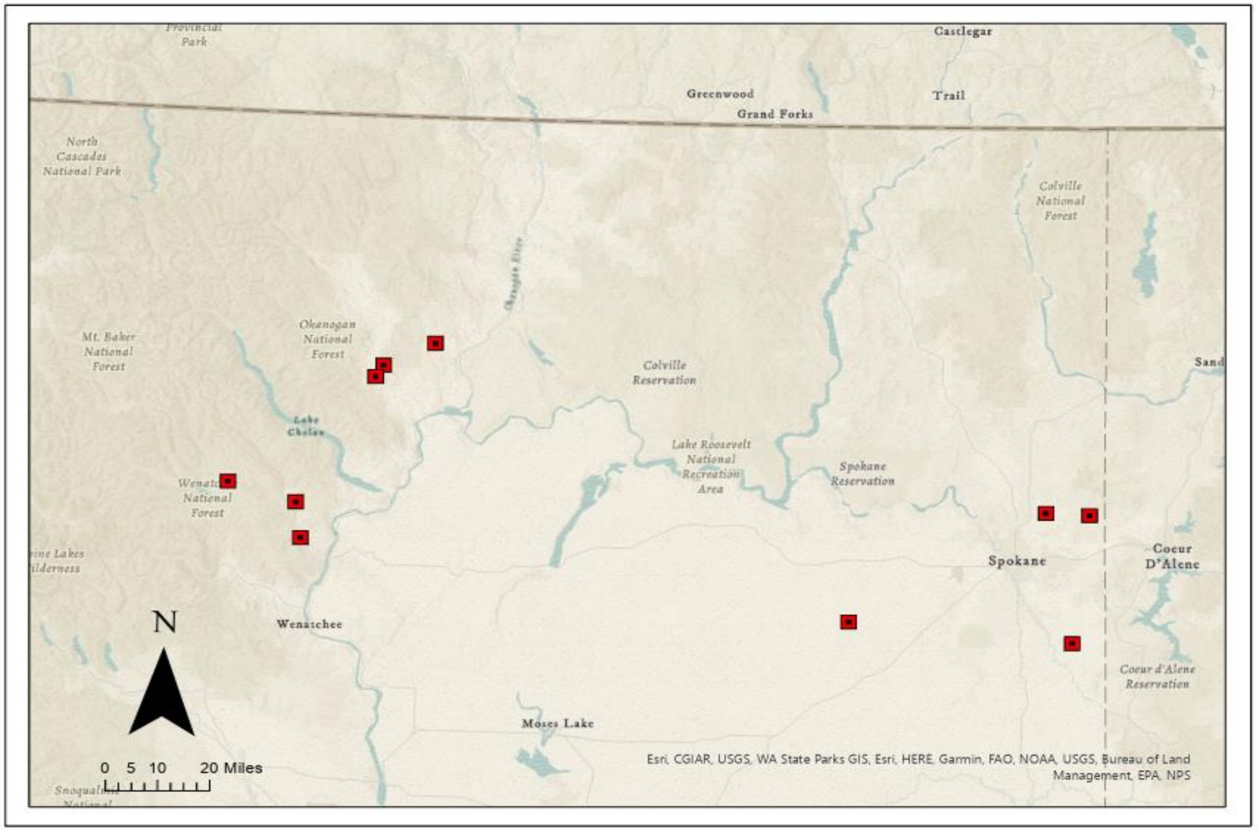

Figure 1. Location of BDA sites across Washington State. Beaver sites not pictured.

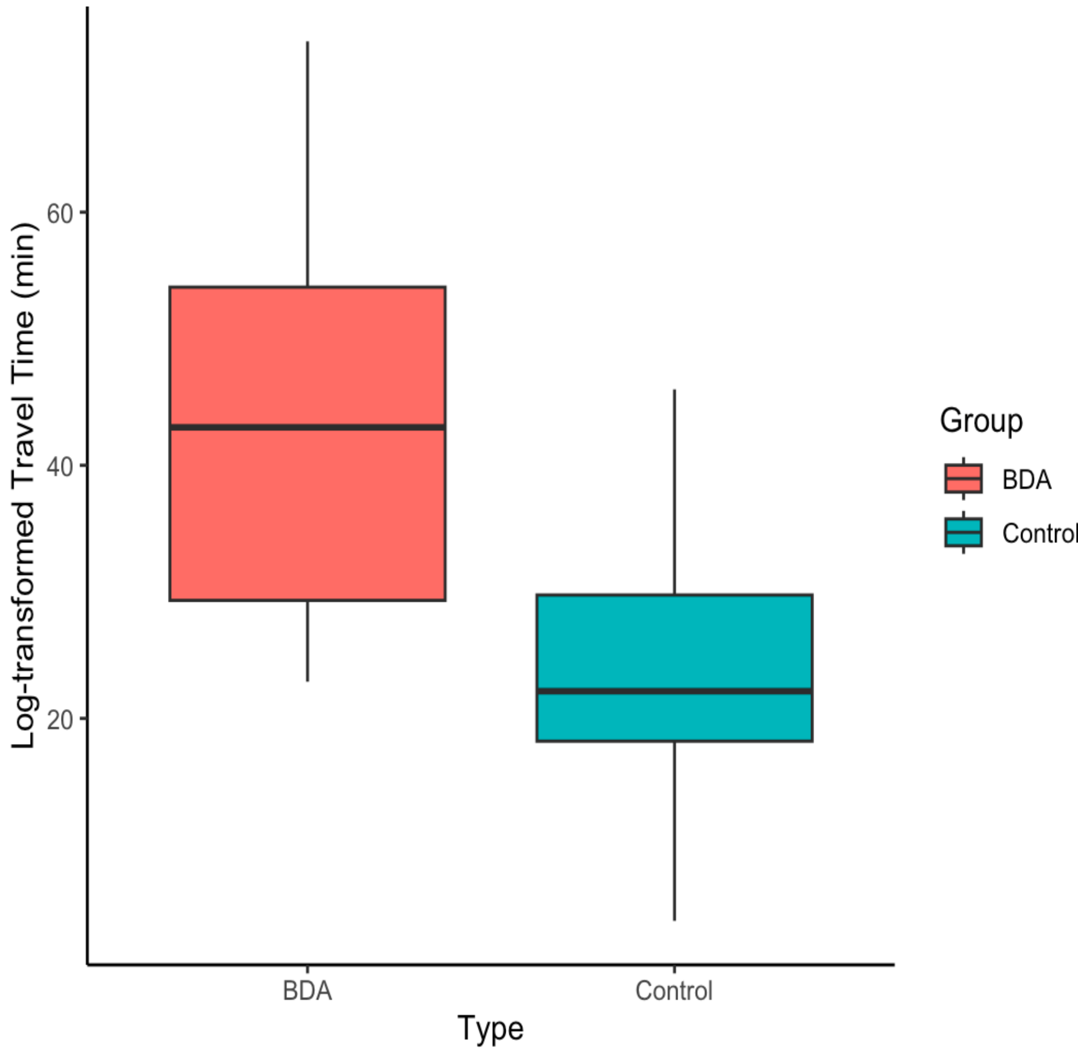

Figure 2: Boxplot showing a log-transformed mean (± se) of the water travel times for 200 m BDA and Control Reaches in semi-arid watersheds of Washington and Idaho, USA.

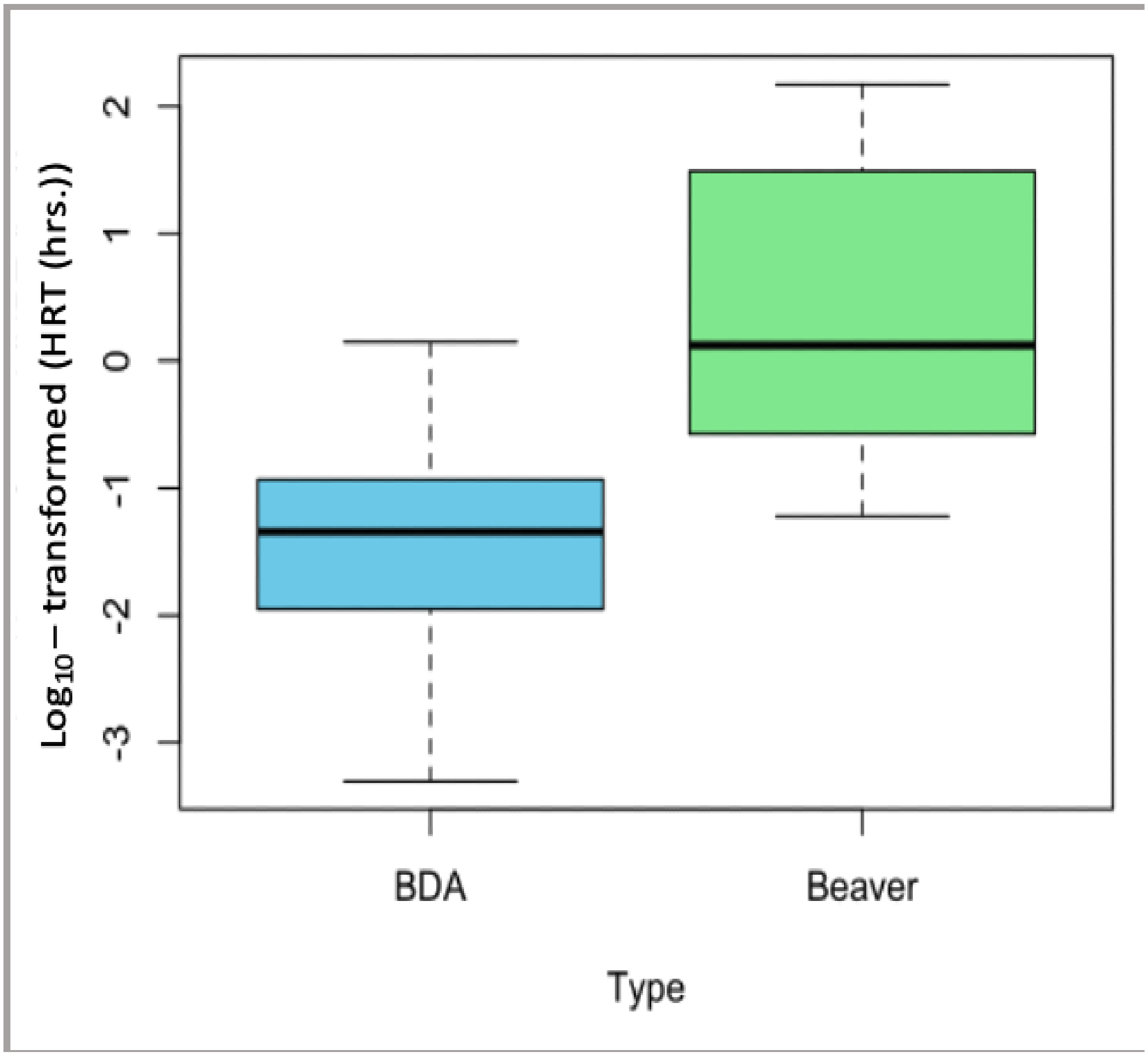

Figure 3. Boxplot showing a $\log_{10}$-transformed mean (± se) of Hydraulic Residence times for BDA and Beaver sites in semi-arid watersheds of Washington and Idaho, USA.

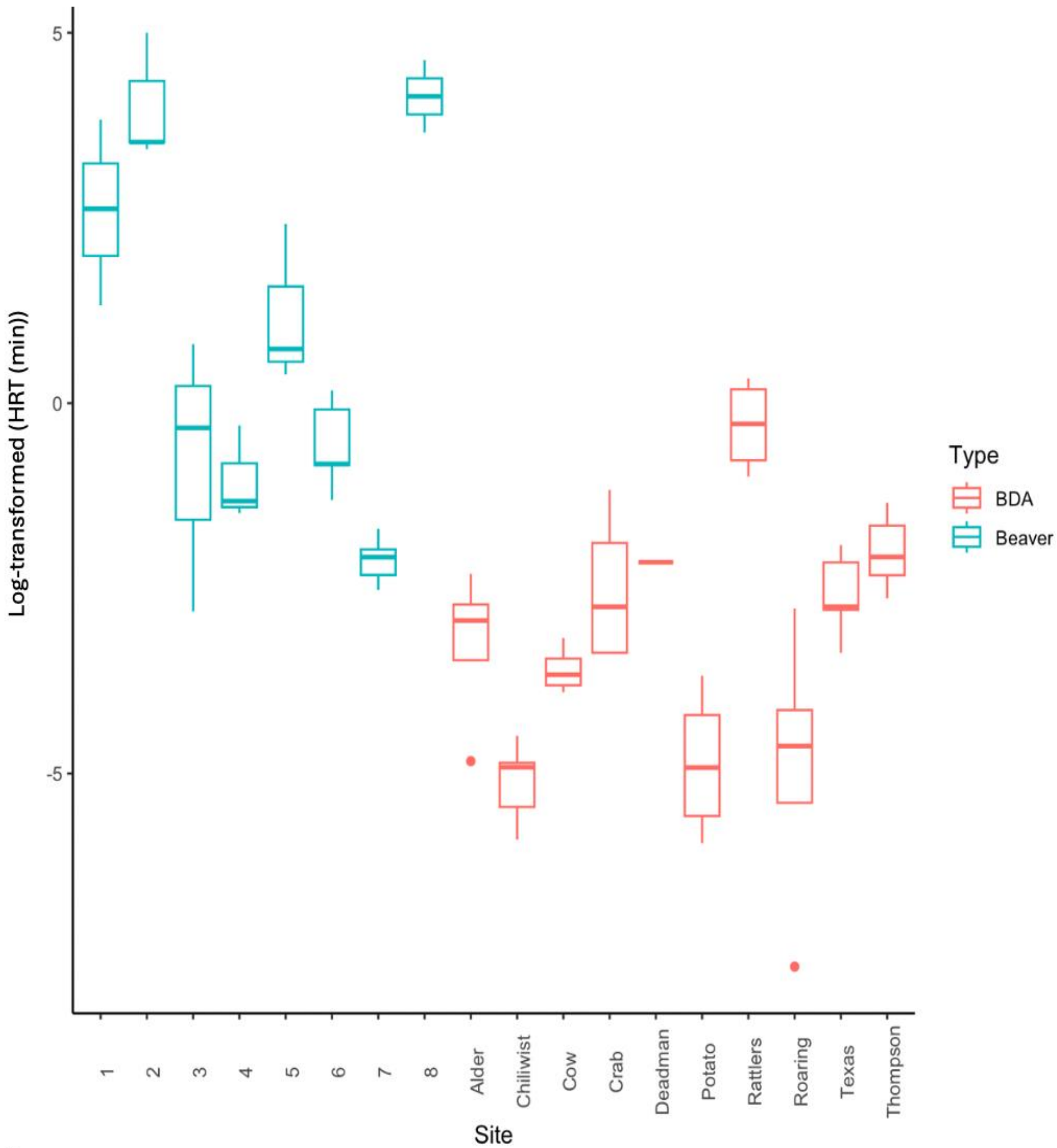

Figure. 4. Log-transformed mean (± se) of Hydraulic Residence times for each BDA and beaver dam site in semi-arid watersheds of Washington and Idaho, USA.

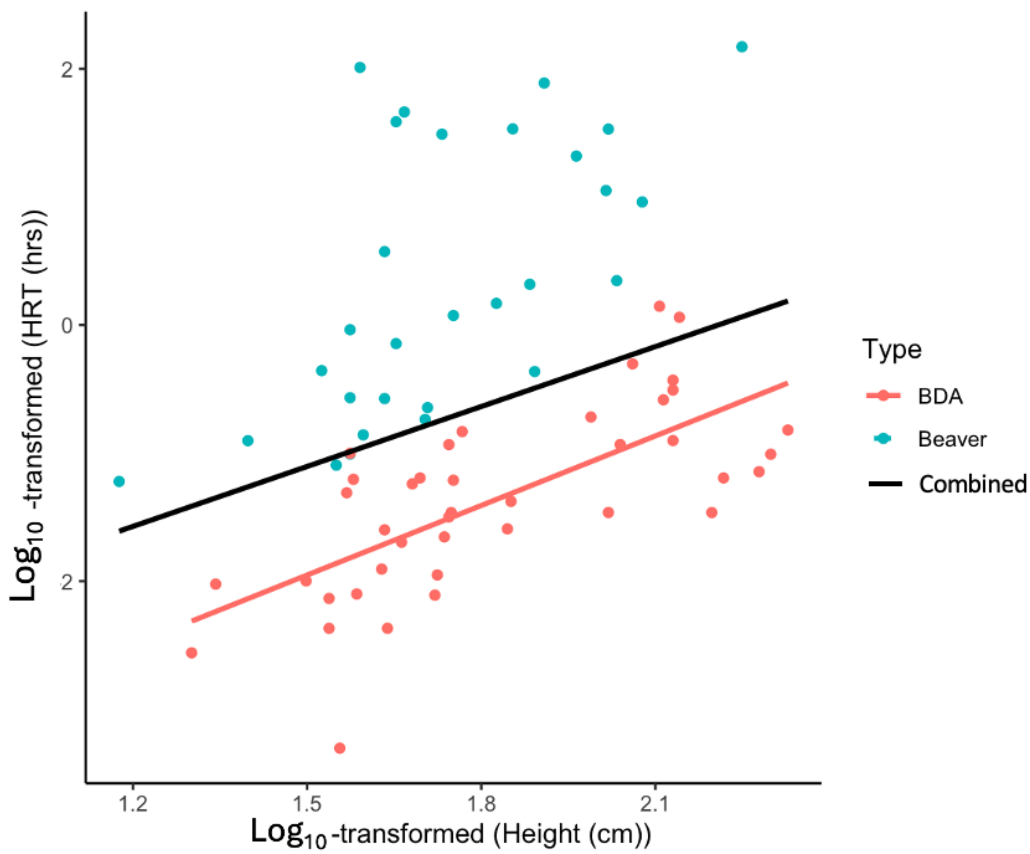

Figure 5. Scatter plot showing the relationship between Log10-transformed Height (cm) and Log10-transformed Hydraulic Residence Time (HRT) (hrs) for Beaver Dams (blue) and Beaver Dam Analogs (BDAs) (red) in semi-arid watersheds of Washington and Idaho, USA. The black line represents the combined regression line for both datasets and the red line represent the regression lines for BDAs.

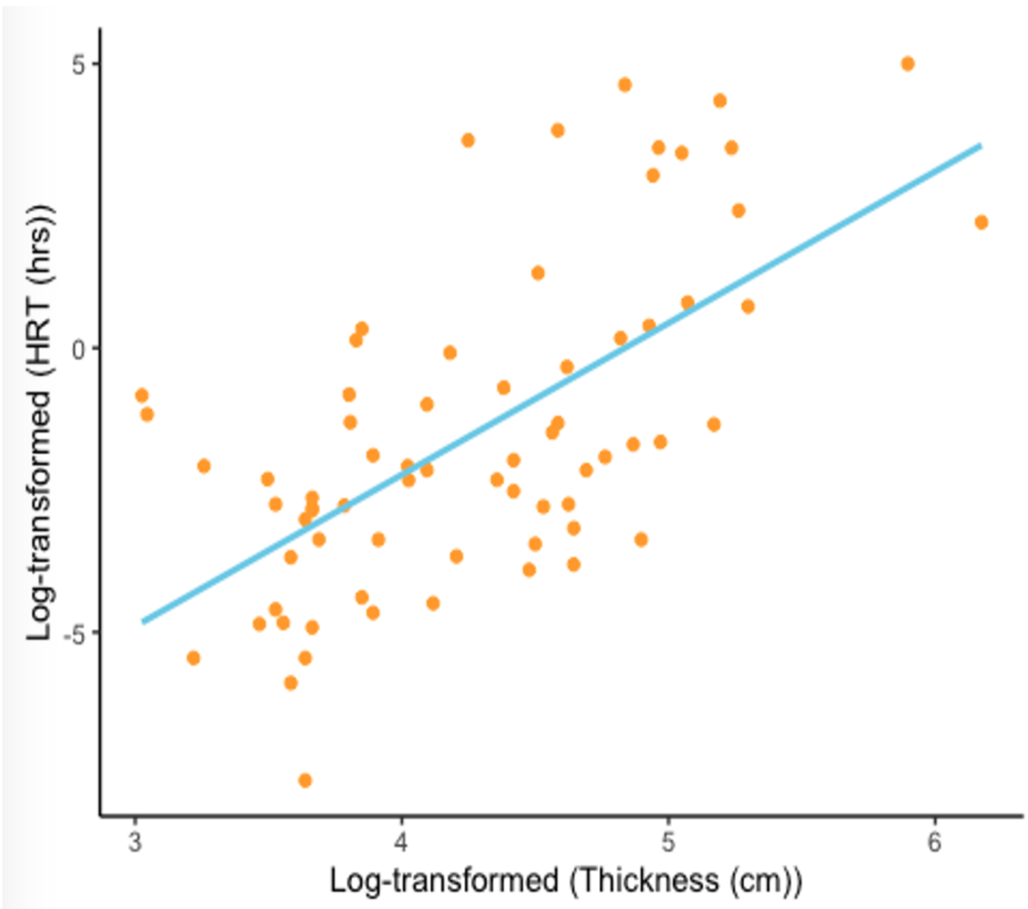

Figure 6. Scatter plot for both dam types showing the relationship between log-transformed hydraulic retention time and log-transformed dam thickness in semi-arid watersheds of Washington and Idaho, USA.

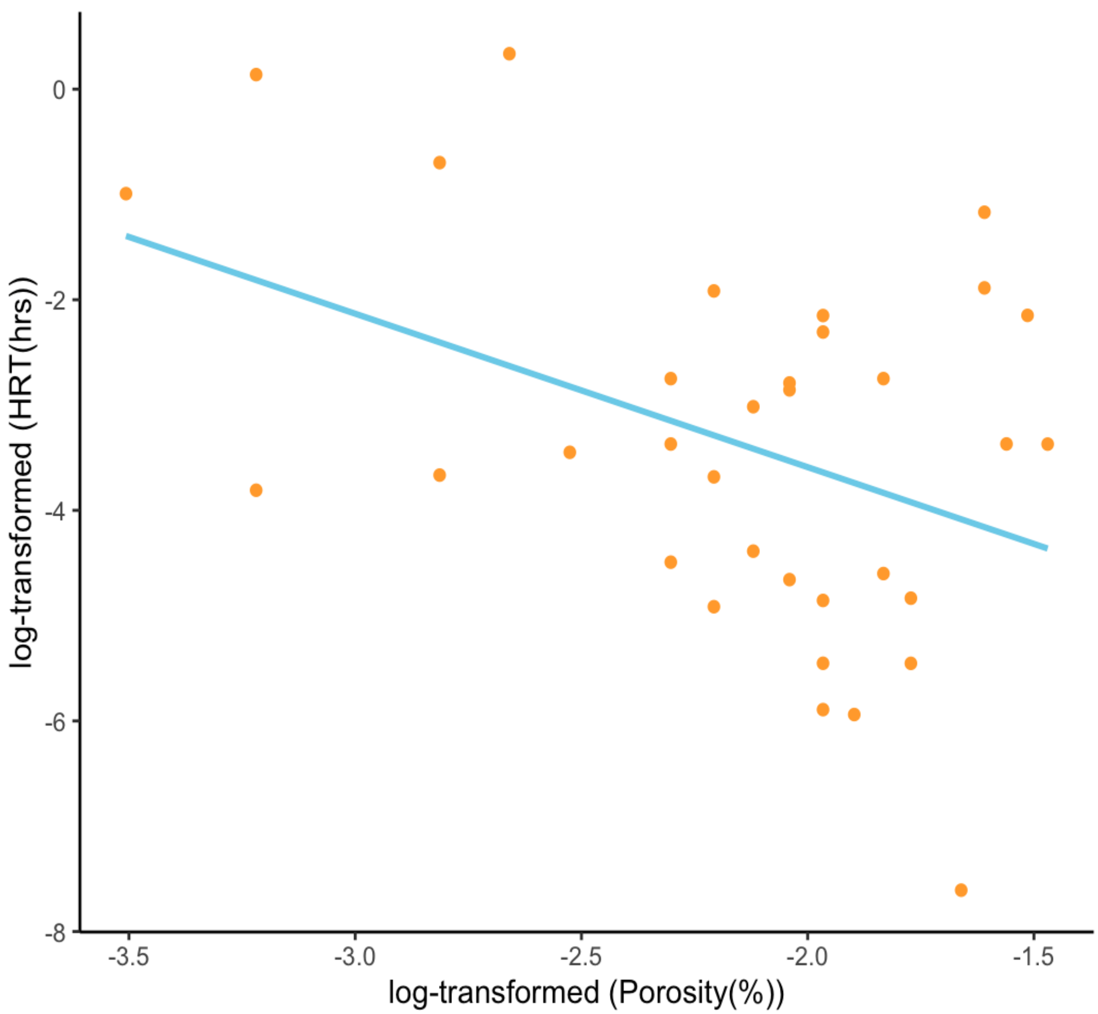

Figure 7. Scatter plot showing the relationship between log-transformed hydraulic retention time and log-transformed porosity for BDA in semi-arid watersheds of Washington and Idaho, USA.

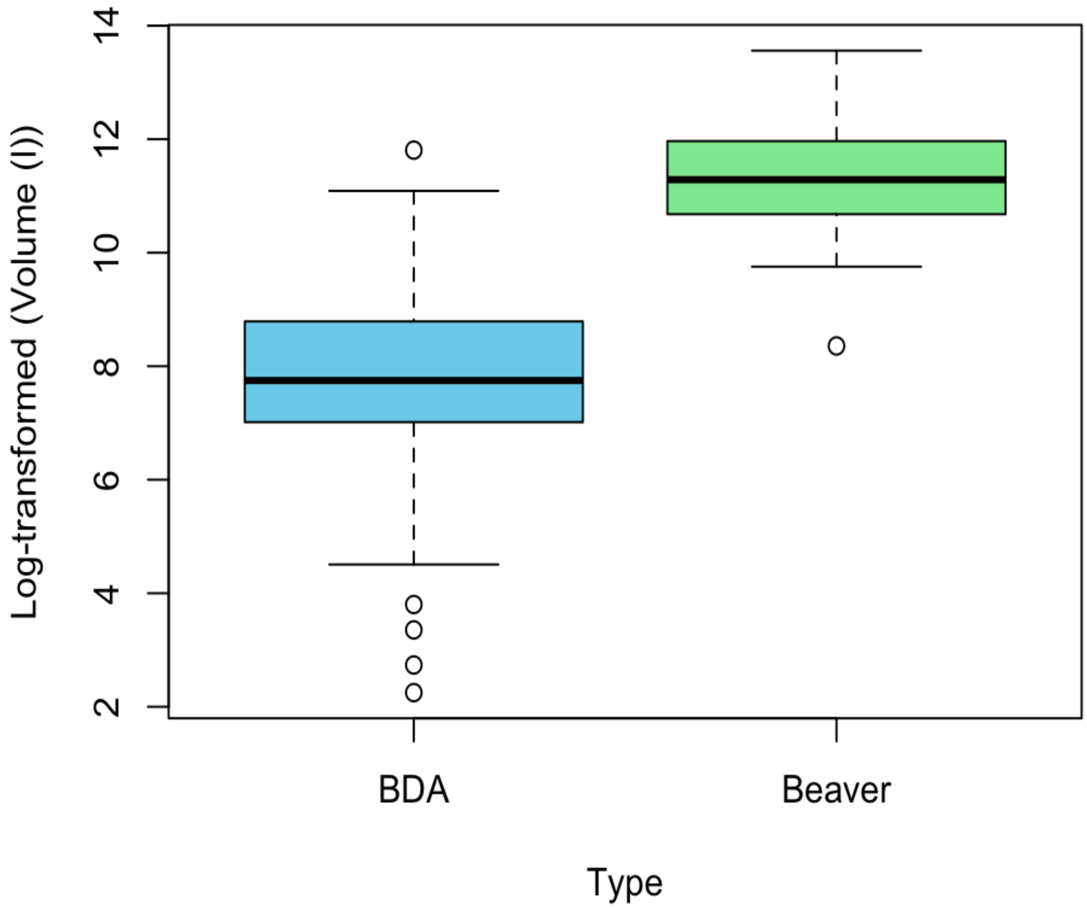

Figure 8. Log-transformed mean (± se) of Pool Volume for each BDA and beaver dam site in semi-arid watersheds of Washington and Idaho, USA.

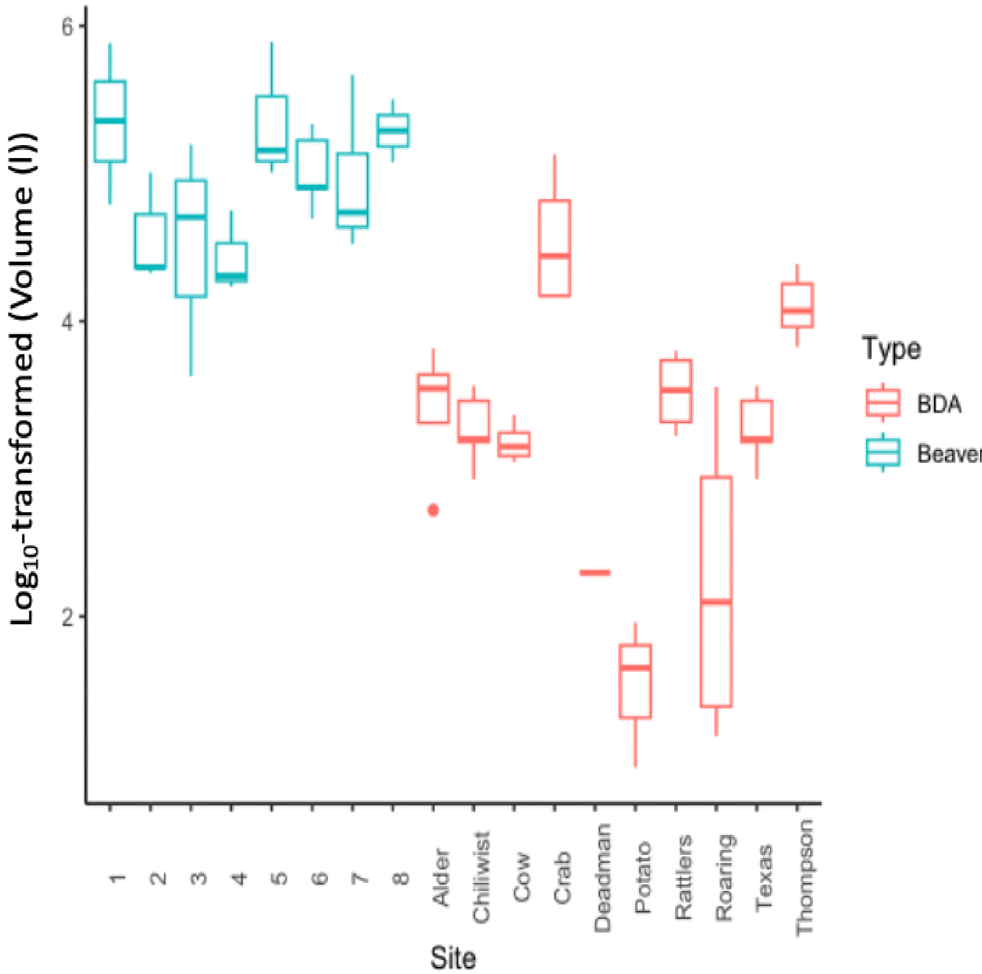

Figure 9. Log_{10}-transformed mean (± se) of pool volumes for each BDA and beaver dam site in semi-arid watersheds of Washington and Idaho, USA.

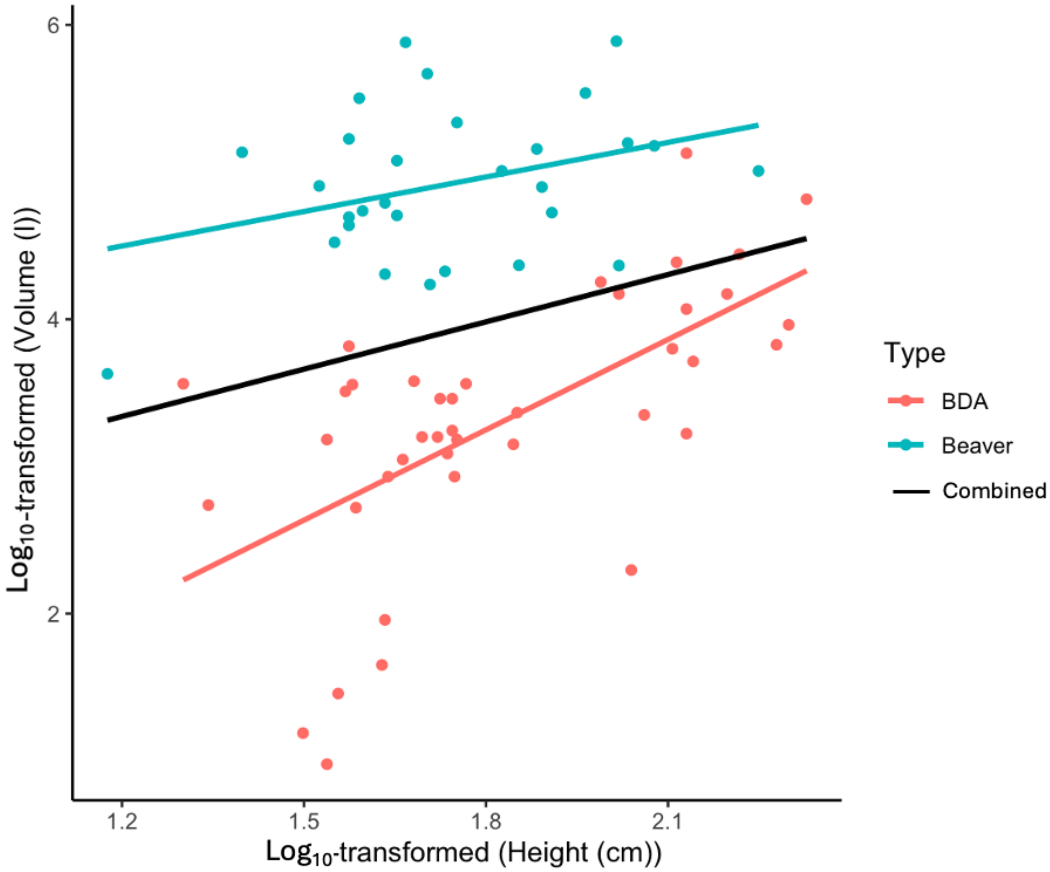

Figure 10. Scatter plot showing the relationship between Log10-transformed Height (cm) and Log10-transformed Volume(l) for Beaver Dams (blue) and Beaver Dam Analogs (BDAs) (red) in semi-arid watersheds of Washington and Idaho, USA. The black line represents the combined regression line for both datasets and the separate red and blue lines represent the regression lines for BDAs and beaver dams, respectively.

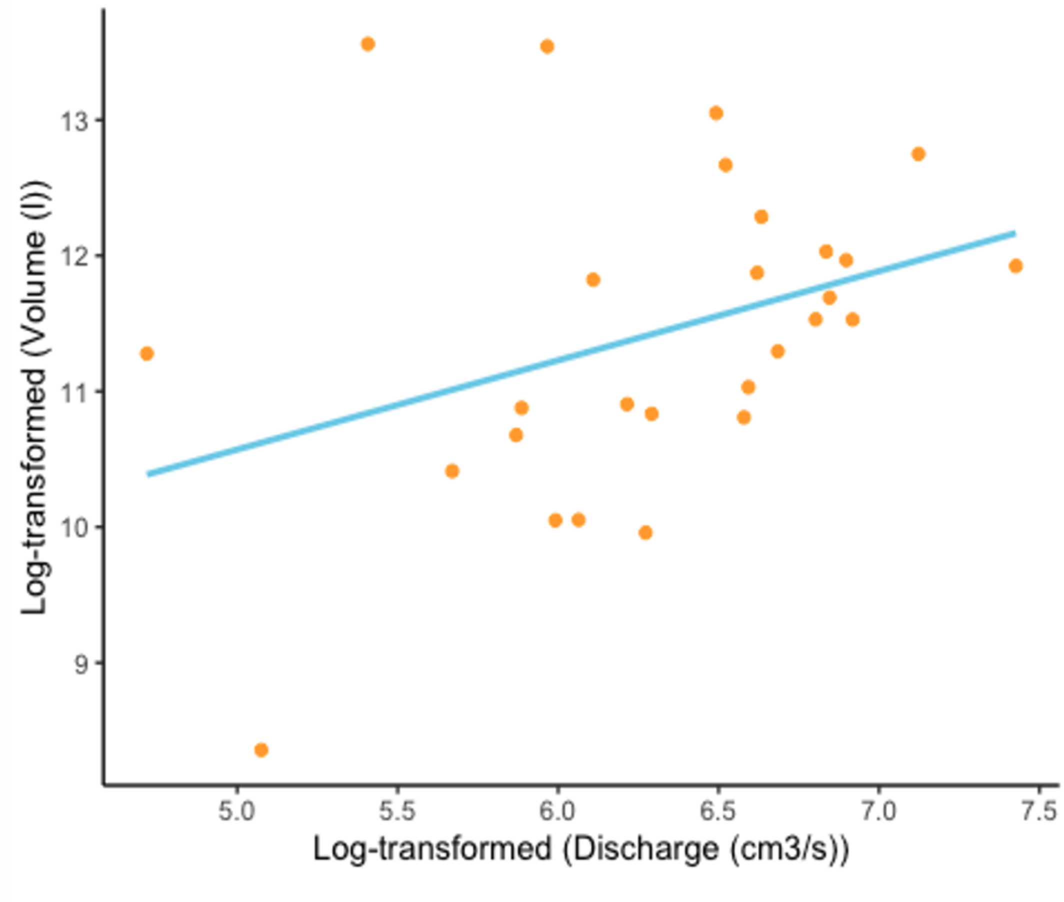

Figure 11. Scatter plot showing the relationship between log-transformed pool volume and log-transformed discharge in beaver dams in semi-arid watersheds of Washington and Idaho, USA.

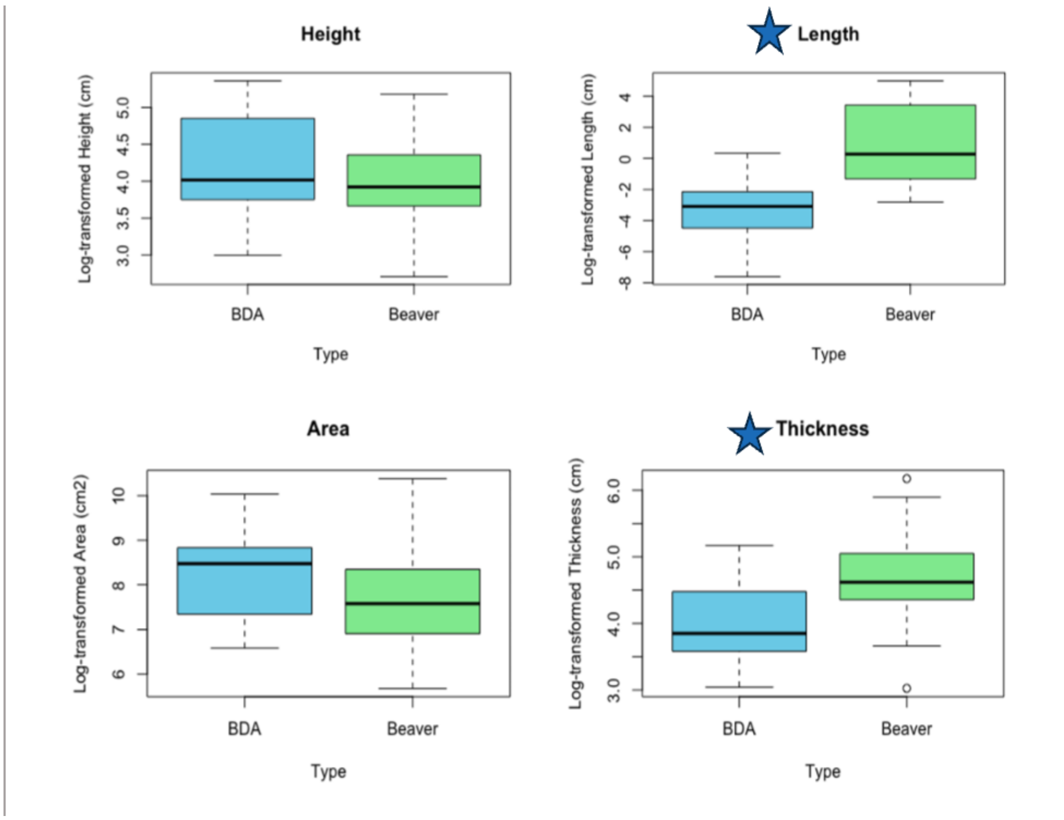

Figure 12. Log_{10}-transformed means (± se) of height, length, area, and thickness for each BDA and beaver dam site in semi-arid watersheds of Washington and Idaho, USA. Significant differences denoted with a star.

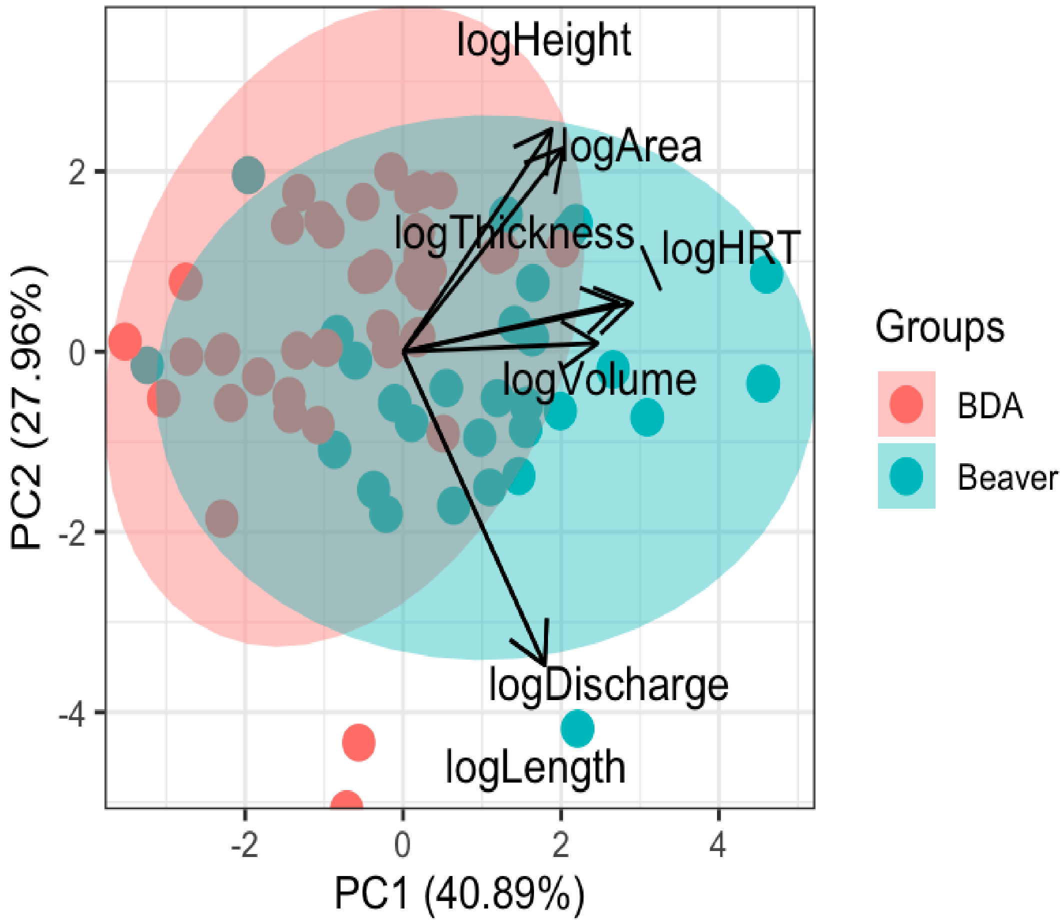

Figure 13: PCA analysis illustrating the variation between Beaver Dam Analogs (BDAs) and Natural Beaver Dams (NBD) based on seven key characteristics: Thickness, Height, Length, Area, Discharge, Pool Volume, and Hydraulic Retention Time (HRT). The first two principal components, PC1 and PC2, capture the majority of the variance in these characteristics. Each point represents an individual dam, with BDAs and NBDs distinguished by different colored ellipses. The positioning of the points reflects differences in dam structures, with the axes indicating the contribution and direction of each characteristic to the variance.

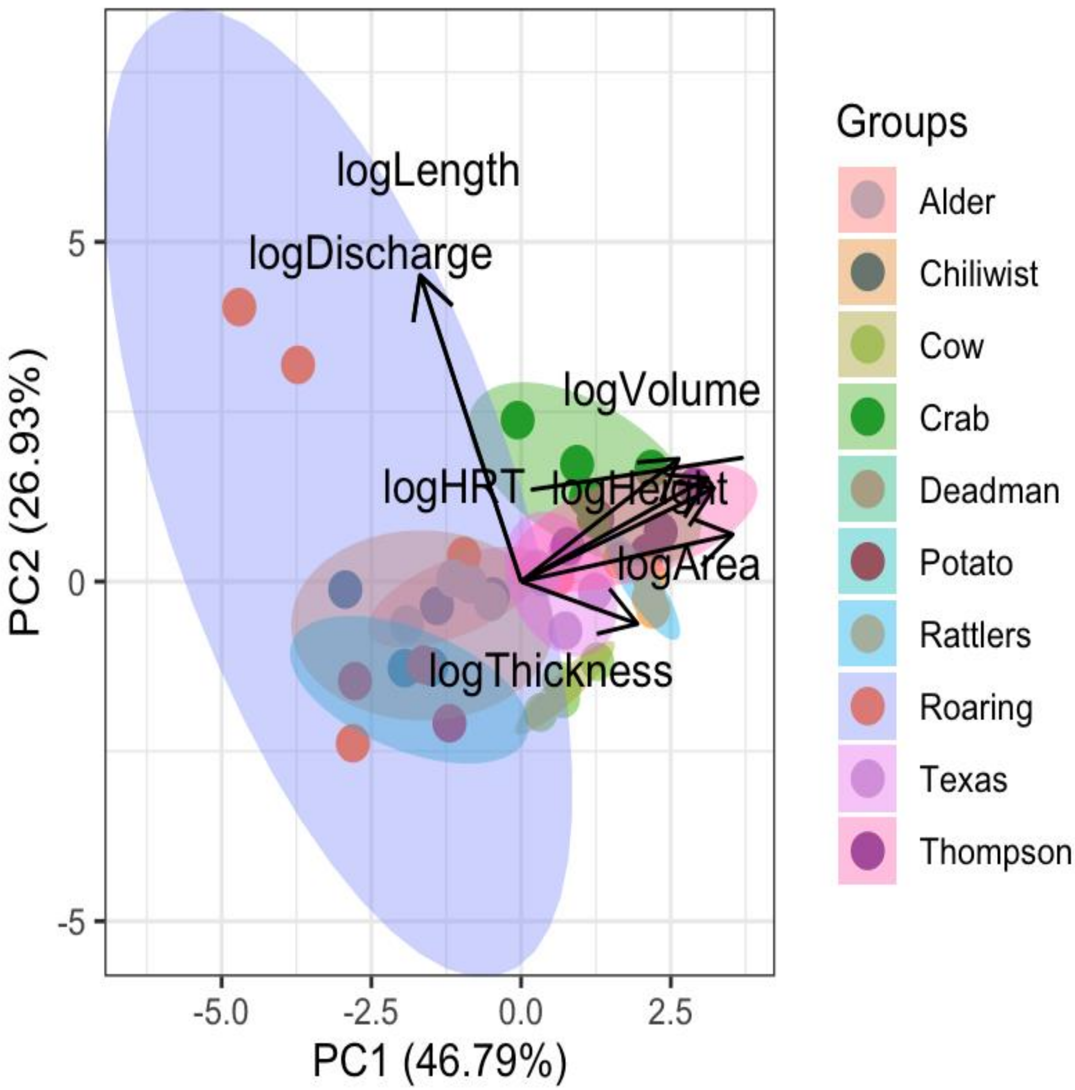

Figure 14: PCA analysis illustrating the variation among Beaver Dam Analogs (BDA) Sites based on seven key characteristics: Thickness, Height, Length, Area, Discharge, Pool Volume, and Hydraulic Retention Time (HRT). Each point represents an individual dam, with sites distinguished by different colored ellipses. The positioning of the points reflects differences in dam structures, with the axes indicating the contribution and direction of each characteristic to the variance.

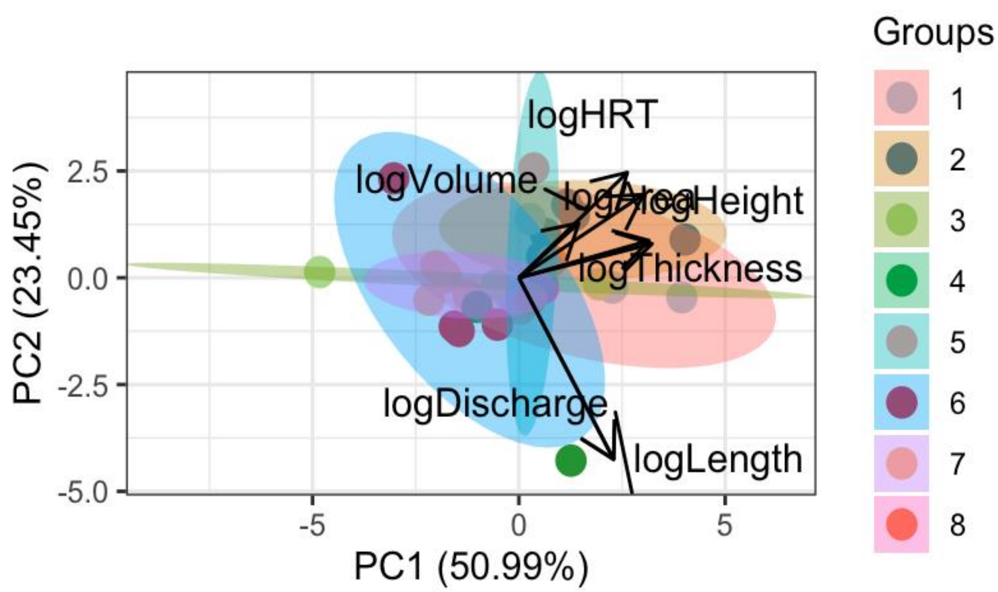

Figure 15: PCA analysis illustrating the variation among Beaver Dam Sites based on seven key characteristics: Thickness, Height, Length, Area, Discharge, Pool Volume, and Hydraulic Retention Time (HRT). The first two principal components, PC1 and PC2, capture the majority of the variance in these characteristics. Each point represents an individual dam, with sites distinguished by different colored ellipses. The positioning of the points reflects differences in dam structures, with the axes indicating the contribution and direction of each characteristic to the variance.

TABLES

Table 1: BDA site information including watershed, watershed area (km), stream order, build date, build materials, number of BDAs and installation team for BDA sites in semi-arid watersheds of Washington and Idaho, USA.

BDA Site	Watershed	Watershed Area(km2)	Stream Order	Build Date	Building Materials	# of BDAs	Installation
Cow	Methow	12.6	3	Winter 2022	Douglas Fir	5	Methow Beaver Project
Texas	Methow	8.43	3	Spring 2022	Ponderosa Pine	5	Methow Beaver Project
Chiliwist	Okanogan	33.34	4	Summer 2022	Ponderosa Pine	5	Methow Beaver Project
Crab	Crab Creek	443	6	Fall 2018/2019	Ponderosa Pine	5	USFWS, NRCS
Deadman	Little Spokane	5.91	1	Fall 2022	Ponderosa Pine	5	Lands Council
Rattlers Run	Hangman	18.87	2	Fall 2019/2021	Pine, mud, sod	4	Lands Council, Gonzaga Univ, USFWS
Thompson	Spokane	31.3	3	Fall 2021	Pine, mud, sod	5	Lands Council, Gonzaga Univ, USFWS
Potato	Entiat	20	3	2020/2022	hardwood, conifer, mud	5	Wenatchee Beaver Project
Roaring	Entiat	60	4	2020	hardwood, conifer, rock	4	Wenatchee Beaver Project
Alder	Wenatchee	13	3	2022	hardwood, conifer, mud	4	Wenatchee Beaver Project

Table 2: Beaver dam site information for beaver dam sites in semi-arid watersheds of Washington and Idaho, USA.

Beaver Site	Watershed	Watershed Area (km2)	Stream Order	#of Dams
1	Methow	18.76	3	5
2	Methow	22	4	5
3	Okanogan	38	5	3
4	Okanogan	334.7	5	2
5	Wenatchee	13	3	3
6	Wenatchee	106	4	5
7	Clearwater	31	4	5
8	Palouse	35	4	2

Table 3. Travel time measurements for each BDA site and its paired control reach in semi-arid watersheds of Washington and Idaho, USA.

Site	Type	Travel time (min)
Cow	BDA	22.9
Cow	Control	14
Texas	BDA	50
Texas	Control	19.6
Chiliwist	BDA	24.3
Chiliwist	Control	20.3
Alder	BDA	40
Alder	Control	32
Roaring	BDA	31
Roaring	Control	24
Deadman	BDA	66.3
Deadman	Control	4
Thompson	BDA	73.5
Thompson	Control	46
Crab	BDA	46
Crab	Control	29

Table 4. Mean thickness, length, height, area, hydraulic residence time, pool volume and porosity for beaver dam complex and BDA sites in semi-arid watersheds of Washington and Idaho, USA. Mean porosity was not measured in beaver sites.

Type	**Mean Thickness (m)**	**Mean Length (m)**	**Mean Height (m)**	**Mean Area (m2)**	**Mean HRT (hrs)**	**Mean Volume (m3)**	**Mean Porosity (%)**
BEAVER	1.25	6.70	0.61	0.41	71	160.9	N/A
BDA	0.61	5.89	0.81	0.5	0.13	7.99	12.9

Table 5. Mean thickness, length, height, area, hydraulic residence time, pool volume and discharge for each BDA site in semi-arid watersheds of Washington, USA.

Site	Type	Thickness (cm)	Length (cm)	Height (cm)	Area (cm^2)	HRT (hr.)	Volume (l)	Discharge (l/s)
Cow	BDA	91	209	59	5,380	0.03	1,560	15.30
Texas	BDA	111	426	55	6,120	0.09	2,100	6.88
Chiliwist	BDA	39	398	41	1,570	0.007	226	9.4
Roaring	BDA	41.3	2320	32	1,310	0.02	1,190	16
Potato	BDA	40	278	44	1,750	0.01	40	1
Alder	BDA	36.3	408	40	1,460	0.05	3,530	18.3
Crab	BDA	38	642	160	6,190	0.1	51,400	120
Thompson	BDA	88.2	444	150	13,300	0.15	14,000	26
Deadman	BDA	61.4	492	100	6,140	0.02	0.20	3.3
RattlersRun	BDA	66	270	124	8,170	0.85	3,840	1.25

Table 6. Mean thickness, length, height, area, hydraulic residence time, pool volume and discharge for each Beaver site in semi-arid watersheds of Washington and Idaho, USA.

Site	Type	Thickness (cm)	Length (cm)	Height (cm)	Area (cm^2)	HRT (hrs.)	Volume (l)	Discharge (l/s)
1	Beaver	191	1150	76	7,270	20	329,000	4.6
2	Beaver	206	546	98	10,100	65	444,000	0.19
3	Beaver	100	563	56	2,800	1	70,800	19.7
4	Beaver	82	550	47	1,930	50.4	31,200	21.1
5	Beaver	177	624	82	7,290	5	340,000	19.2
6	Beaver	60	664	49	1,450	0.7	119,000	50.7
7	Beaver	86	451	38	1,620	407	147,000	0.1
8	Beaver	98	810	42	2,060	70.6	219,000	0.86

Table 7. Type 2 ANOVA Analysis of Multiple Linear Regression Models to Evaluate the Effect of dam dimensions on HRT and pool volume for BDA and beaver dam site in semi-arid watersheds of Washington and Idaho, USA. This table summarizes the ANOVA results, focusing on the comparison of model effects and significant factors impacting HRT and pool volume. Significance levels are denoted as *p<0.05.

Dependent Variable	Source of Variation	SS	df	MS	F value	p-value
HRT ALL	logHeight	70.5	1	70.5	30.9	5.298e-07*
	logThickness	18	1	17.9	7.9	0.0066 *
	Type	154	1	154	67.4	1.118e-11*
	Residuals	150.7	66	2.29		
HRT BDA	logHeight	44.2	1	44.2	34	2.241e-06*
	logPorosity	9.70	1	9.7	7.46	0.0105*
	Residuals	39.0	30	1.3		
HRT Beaver	logThickness	8.56	1	8.56	2.27	0.144
	logHeight	12.5	1	12.5	3.31	0.0805*
	Residuals	98	26	3.77		
Volume ALL	logHeight	63	1	63.3	29.3	9.34e-07*
	Type	271	1	271	125	2.2e-16*
	logHeight: Type	8.26	1	8.26	3.82	0.0549
	Residuals	143	66	2.16		
Volume BDA	logHeight	44.2	1	44.2	34	2.241e-06*
	logPorosity	9.7	1	9.7	7.46	0.0105*
	Residuals	39	30	1.3		
Volume Beaver	logHeight	5.91	1	5.91	5.75	0.0254*
	logDischarge	6.53	1	6.53	6.35	0.0195*
	logK	1.65	1	1.65	1.61	0.218
	logHeight: logDischarge	5.41	1	5.41	5.27	0.0317*
	Residuals	22.6	22	1.03		

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Sawyer Nagle, MS
crowbirdly@gmail.com

University Education

2022-2024 **MSc, Biology**
Eastern Washington University, Cheney, Wa

Thesis: The Roles of Dam Dimensions and Surface Porosity on the Water Storage Capacity of Beaver Dam Analogs Compared to Natural Beaver Dams

2018-2022 **BSc, Ecology**
The Evergreen State College, Olympia, WA

Coursework:
Applied Wetland Monitoring Science, Hydrology, Freshwater Ecology, Aquatic Chemistry, Aquatic Entomology, Forest Ecology, Soil Science, Ecosystem Ecology, Graduate Research Methods, GIS, Remote Sensing (Drones and Lidar) and Statistics

Analytical Methods:
Ion Chromatography (Dionex IC25A) & Diode Array Uv-vis Spectrophotometer (Agilent 8453). Microscopy: Leica DM500 & Leica EZ4W, YSI 2030 and 556 (use and calibration), Oakton pH meter (use and calibration), Swoffer Flow Meter (Model 2100), Hach FH950 Flow Meter, 152 H hydrometer, LaMotte turbidity meter, Alpkem 3 Flow Analyzer, Aquafluor handheld meter (Turner Designs)

Software:
Microsoft Suite, Google Suite, JMP Pro 15, Arc GIS Pro/Arc GIS online, Drone2Map, Avenza, Rstudio, ImageJ

Honors & Awards

2024	Phi Kappa Phi Honor Society
2020-2021	Lee Hoeman Scholarship, The Evergreen State College, $1950
2020-2021	Girvin Family 2 Scholarship, The Evergreen State College, $1435
2018-2019	Bennett Scholarship, The Evergreen State College, $1736

Professional Experience

8/22-6/24 **Graduate Research Assistant (field and lab)**

Collected hydrological, topographical, soil and vegetation data for a long-term beaver dam analog restoration project in Washington State.

9/21-12/21 **Program Aide, Forests, Evergreen State College**
Created a collection of dissection powerpoints of local bryophyte species, collected bryophyte specimens, and assisted students with lab ID.

6/21-9/21 **Field Biologist, Wetland monitoring internship, Washington Dept. of Transportation**
Fieldwork included conducting surveys of vegetation, plant ID, hydrology and wildlife at several WSDOT wetland mitigation sites.

1/21-6/21 **Teaching Assistant, Field Plant Taxonomy and Conservation, Evergreen State College**
Supported the bryophyte portion of this upper-division program by collecting specimens, tutoring students in using dichotomous keys, accompanying field identification walks and grading.

6/20-9/20 **Program Aide, PNW Plant Identification and Plant Biology, Evergreen State College**
Supported both programs by identifying, collecting and distributing plant specimens to students once a week. Created master plant keys, using Flora of the Pacific Northwest, as a teaching tool for the professor.

Presentations

- Nagle, S., K. Killoy**,** A. Whipple, R. Brown, J. Weirich, and C. McNeely. “Are beaver dam analogs an effective restoration strategy for ecosystem function in wildfire-impacted, cold, semi-arid watersheds?” (2023) - **Oral (Society of Wetland Scientists Conference)**

- Nagle, S., R. Brown, B. Buchanan, C. McNeely. “The roles of porosity and hydraulic conductivity on the efficacy of beaver dam analogs (BDAs) (2023) - **Poster (Ecological Society of America Conference)**

- Nagle, S. “The roles of dam dimensions and surface porosity on the water storage capacity of beaver dam analogs compared to natural beaver dams" (2024)- **Oral (Wildlife Society Joint Annual Meeting)**

Certifications

2024 Geographic Information Systems (GIS) Graduate certificate, Eastern Washington University

2013 Advanced Permaculture Certificate in Forestry, Siskiyou Permaculture Institute

2005 Permaculture Design Certificate, Portland Permaculture Institute

Professional Involvement

2024 **Session Organizer, Washington Chapter of the Wildlife Society Joint Annual Meeting, (2024**)

- Organized a dedicated session on beaver-based restoration and management, bringing together experts and researchers in the field.

2023 **Panel of Stakeholders for Stream Restoration Project**
Dr. Sue Niezgoda, Gonzaga University

- Participated as an online stakeholder in the Thompson Creek Stream Restoration Project, guiding students in developing adaptive management recommendations and conceptual designs for Beaver Dam Analogs (BDAs).