ASSESSING BIOTA AND ENVIRONMENTAL CHARACTERISTICS ABOVE AND BELOW A LOW-HEAD DAM

A thesis presented to the faculty of the Graduate School of Western Carolina University in partial fulfillment of the requirements for the degree of Master in Biology

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

- EPT - Ephemeroptera, Plectoptera, and Trichoptera
- Bed per – Bedrock percentage
- Bdr per – Boulder percentage
- Cob per – Cobble percentage
- Grv per – Gravel percentage
- Snd per- Sand percentage
- Slt per – Silt percentage
- Wd per- Woody debris percentage
- Avg WW - Average Wetted Width
- Chain Ro – Chain Roughness
- rkm – river kilometers
- PCA – Principal Components Analysis
- ANOSIM – Analysis of Similarities
- SIMPER – Similarities Percentages
- EB – Extreme Below
- CB – Center Below
- CA – Center Above
- EA – Extreme Above
- BV- Bottom Velocity
- CV- Column Velocity

- PC1- Principal Components 1
- PC2 - Principal Components 2
- nMDS – Non-metric Multi-Dimensional Scaling

ABSTRACT

ASSESSING BIOTA AND ENVIRONMENTAL CHARACTERISTICS ABOVE AND BELOW A LOW-HEAD DAM

Trevor Lane Alexander

Western Carolina University (June 2023)

Dams are a form of anthropogenic alteration to aquatic ecosystems that can affect natural conditions and influence aquatic fauna assemblages. Depending on the size and type of a dam, the resulting effect on the aquatic environment will differ. Possible effects include altered flow rate, water temperatures, and sediment transport. Dams can also create barriers that limit fish migration or distribution of fishes, macroinvertebrates, and aquatic plant species. The focal point of this study was a low head dam, located on the Tuckasegee River in Jackson County, NC. This dam is damaged and will possibly be removed in the future. We sampled fish and macroinvertebrates at multiple sites above and below the dam to compare species assemblages. We collected benthic macroinvertebrates using a kick net in shallow riffles and a D-frame net for timed multihabitat sampling. We used backpack electrofishers to sample fish in available wadeable habitats. We used multivariate statistical analyses to determine similarity of fish and macroinvertebrate assemblages among sites. Our results indicate that the dam has had minimal effects on aquatic habitat and aquatic macroinvertebrates. We found greater fish diversity below the impoundment. We detected some species only above or below the dam. Based on the results of this study, we believe that restored connectivity to this system may improve fish diversity above the dam. Removing the dam may cause a temporary decrease in sensitive macroinvertebrates since the dam retains sediment. Substrate composition may change

temporarily below the dam until the finer substrate is transported downstream. Overall, this study provides baseline data over two years that can be referenced if the dam is removed.

INTRODUCTION

Many anthropogenic alterations to aquatic ecosystems can affect natural conditions and influence aquatic fauna assemblages (Sendzimir & Schmutz, 2018). A few common alterations are the removal of riparian vegetation (Knight & Bottorff, 1984), channelization, diversion of flow, and dams (Poff et al., 1997; Zeiringer et al., 2018). Removal of riparian vegetation may occur due to agriculture or urbanization and can influence water quality by increasing the temperature, nitrate levels, algae levels, sedimentation, and influence flow regimes (Larson et al., 2018). Often rivers are channelized (straightened and deepened) to maximize discharge and minimize flooding. The natural flow regime and water depth changes can reduce aquatic habitat diversity (Sendzimir & Schmutz, 2018). Channel diversion (redistribution of water) can have varying physical and ecological impacts, such as accelerated erosion, sediment deposition, water quality issues, and biodiversity loss (Flatley et al., 2018).

Dams are another form of anthropogenic alteration that can disrupt natural habitat (Allan 1995; Sendzimir & Schmutz, 2018). Man-made dams exist on rivers throughout the world. They are built for a wide array of uses: to create reservoirs to provide drinking water, act as a cooling supply for a power plant, generate power through hydroelectric dams, provide irrigation for agriculture, and create water recreation activities and fisheries (Schmutz & Moog, 2018). The size of dams greatly varies from large hydroelectric dams that impound large reservoirs to low-head, run-of-the-river dams.

Hydroelectric dams are large dams that impound water to create a reservoir to provide water to turn turbines to generate electricity. These dams often release cool water from the hypolimnion, often at high velocities. Hydroelectric dams may release water at different times of the day as needed, causing short-term variation in discharge rates (Allan, 1995). In the winter, hydroelectric dams may release water near 4 degrees Celsius resulting in slightly warmer than normal water temperatures downstream of the dam (Allan, 1995). Top-release dams generally do not produce as significant of a change in water temperature as bottom-release dams. However, in some cases, top-release dams may result in the warming of the downstream river depending on the size of the surface of the reservoir. Dams can often alter dissolved oxygen (DO) levels compared to a free-flowing stream (Allan, 1995). Typically, high levels of DO are found below dams. It is important to note that temperature and DO levels are closely related because cold water can hold more dissolved oxygen than warm water (Harvey et al., 2018). Algal blooms may occur downstream of a bottom-release dam since this portion often contains clear water due to the dam filtering sediment. In addition, the water from the hypolimnion is often cold and oxygen-saturated with high nutrient content, which further promotes algal blooms (Allan, 1995; Simons, 1979). If excessive algal growth occurs, anoxic or hypoxic conditions may occur, consequently decreasing benthic fauna and resulting in fish kills (Allan, 1995; Watson et al., 2016). Typically, altered downstream conditions due to dams return to normal within a few kilometers for a small dam or up to 80 km for a large, bottom release dam (Allan, 1995).

There is abundant research on the effects of large dams on the physical and chemical environment, and on fish and macroinvertebrate aquatic communities, but much less is known about the effects of low-head dams. In recent years, interest has grown in the removal of low-head dams. Many dams are aging and need repairs, so dam removal is considered by those responsible for the dam and is often encouraged by ecologists to restore habitat conditions and connectivity. Pre-dam and post-dam removal data is important to understanding the general effects that low-head dams have on the natural environment and aquatic communities and to better understand how the removal of low-head dams may affect the natural environment for restoration projects. The United States Army Corps of Engineers have listed 91,759 large dams within the United States in their national inventory, with an average dam age of 61 years old (USACE 2013). However, it is estimated that approximately 2,000,000 low-head dams exist in the United States alone (Fencl et al., 2015).

Low-head dams are usually < 7.6 m tall (Fencl et al., 2015) and release water at the rate that it enters the reservoir, and usually have minor adverse effects (Allan, 1995). These low-head dams are typically much shorter than the top of their adjacent banks and may become fully submersed during high flow periods. The dam increases the water surface level and provides enough water depth for raw water intakes or turbines to turn even during low flow periods (Csiki & Rhoads, 2010).

The effects of low-head dams on the natural environment vary depending on the channel geometry, the river's slope, and the dam's height (Fencl et al., 2015). The number of upstream dams and the distance between dams may influence the effect of a low-head dam on river habitat (Fencl et al., 2015). For example, the downstream habitat alteration of a dam is inversely related to the number of upstream dams and positively correlated to the distance of the closest neighboring dam (Fencl et al., 2015), which means that a dam located downstream of multiple dams with a close neighboring dam has a shorter distance of downstream habitat alteration before returning to more natural characteristics.

Habitat alterations caused by low-head dams are generally unique to each dam; therefore, it can be difficult to point out general trends. For example, in a review of the effects of low-head dams, Fencl et al. (2015) reported that some, but not all studies found a significant increase in wetted width above some low-head dams. Another study saw a general but insignificant increase in the wetted width above low-head dams (Skalak et al., 2009). Conversely, Csiki and Rhoads (2014) saw an increase in wetted width below low-head dams. The researchers speculated that the dam likely caused high amounts of downstream bank erosion, widening the channel (Csiki & Rhoads, 2014). Low-head dams typically produce a pool of slow-moving water upstream of the dam. There is usually finer substrate, such as sand and silt, located upstream of low-head dams due to settling in slower-moving water. The substrate downstream of dams is comprised of a combination of pebble, gravel, and cobble (Fencl et al., 2015; Csiki & Rhoads, 2014; Skalak et al., 2009). It is common to see a deep plunge pool below these dams with increased water velocity immediately below the dam, known as a hydraulic jump (Fencl et al., 2015). This increase in velocity often carries small substrate downstream and typically results in larger substrate found immediately below the dam (Fencl et al., 2015). However, sediment size-structure returns to that typical of upstream areas with increased distance downstream from the dam. Typically, there is a transition from a larger substrate below the dam to an increase of silt and sediment as you progress farther downstream of the dam. According to the Fencl et al. (2015) study, this change can be seen in as little as 1.2 km below a low-head dam, while the average distance for change is approximately 6.7 km.

Researchers often sample benthic macroinvertebrates as a part of water quality sampling to better understand the health of a riverine system (Bredenhand & Samways, 2009). In this study, we sampled macroinvertebrates above and below a low-head dam to see if there was a difference in assemblages associated with the dam in addition to collecting baseline, pre-dam removal data. Macroinvertebrates are often used for water quality assessments since they are readily found in a range of habitats, have varying responses to environmental stress among and within species, are relatively sedentary, and do not move as much as fish allowing for the ability to understand localized changes in environments (Rosenberg & Resh, 1993). The sampling of macroinvertebrates can provide evidence of current and past changes to their environment, whereas water quality assessments only show the conditions during sampling (Merritt & Cummins, 2008). Some macroinvertebrate species or families are more sensitive to environmental stressors; for example, the gilled forms of Ephemeroptera, Plecoptera, and Trichoptera are the most affected by waters with low dissolved oxygen concentrations which usually are present in polluted areas (Gaufin & Tarzwell, 1956). The richness of EPT (Ephemeroptera, Plecoptera, and Trichoptera) has often been used to assess the water quality of an area. These taxa are usually pollution sensitive and are easier to correctly identify than other aquatic insect taxa (Merritt & Cummins, 2008). The presence of macroinvertebrates with low tolerance to temperature, DO, sedimentation, and other physicochemical alterations can indicate a healthy environment. In contrast, the absence of sensitive macroinvertebrates can give researchers a better understanding of degraded or limiting environmental conditions.

Bredenhand & Samways (2009) sampled macroinvertebrates above and below a dam in an area deemed a biodiversity hotspot. They found significant differences in the relative abundance of five out of nine benthic macroinvertebrate orders, including Annelida, Coleoptera, Ephemeroptera, Plecoptera, and Trichoptera, when comparing the upstream versus downstream sites. The portion of the river downstream of the dam had lower macroinvertebrate density compared to the upstream site (Bredenhand & Samways, 2009). Shredders were more abundant upstream of the dam due to a narrower channel and denser tree canopy. In contrast, grazers and filter feeders were in highest abundance downstream of the dam, where algal growth was highest due to the slow-moving water (Bredenhand & Samways, 2009). According to Vannote et al. (1980), their study area should have consisted primarily of shredders and collectors. However, the dam slowed the water enough to increase algal abundance, resulting in an atypical increase of grazers compared to similar free-flowing rivers.

Most studies focus on the effect of larger dams on instream habitat and diversity, but few studies address the effects of small, low-head dams. A literature review by Mbaka and Mwaniki (2015) analyzed 94 papers focusing on the effects of small impoundments on physical and chemical habitat conditions and the effects on macroinvertebrates. They discovered minimal significant effects on most physicochemical variables, but the dam usually affected macroinvertebrate richness and density (Mbaka & Mwaniki, 2015). Tiemann et al. (2005) found similar results of differing EPT percentages relative to other macroinvertebrate taxa collected from gravel bars centered around two low-head dams; the mean EPT percentages were greater at reference sites, which were free-flowing sites and assumed to have minimal effect by the dam when compared to the immediate upstream treatment site. There was no statistical difference between the reference sites and the site immediately downstream of the dam. However, EPT percentages were significantly greater at reference sites than at upstream treatment sites (Tiemann et al., 2005).

The researchers found two significant positive correlations (stream velocity and % gravel in the substrate) and two negative correlations (boulder and % substrate compaction in the substrate) with EPT percentage (Tiemann et al., 2005). EPT percentages were greatest in areas with the highest stream velocity with predominately gravel substrate, while boulders and compact substrate decreased EPT percentage. Tiemann et al. (2005) hypothesized that the negative correlation between EPT percentage and substrate embeddedness could be related to sediment filling in the stream bed above the dam and subsequently decreasing habitat for EPT in addition to the other instream effects caused by dams mentioned previously.

Often dams will fragment watersheds by prohibiting the upstream movement of fishes, consequently leading to a decreased species richness upstream of the dam, especially if migratory fishes are present (Reyes-Gavilan et al., 1996; Holmquist et al., 2008; March et al., 2003). Low-head dams as small as 1.5 meters tall can significantly restrict fish movement (Gillette et al., 2005). In Porto et al. (1999), only 3 species (Rainbow Trout, Chinook Salmon, White Sucker) out of 42 were able to bypass low-head barriers. Some species of Salmonids, such as listed in the previous study are known to jump to traverse barriers (Resier & Peacock, 1985, as cited in Porto et al., 1999). The mean length of individuals that traversed the low-head dams in the Porto et al. (1999) study was 427 mm. This finding supported their hypothesis that larger fish were more likely to bypass low-head dams easier than smaller fish. There was a significant reduction in species richness of fish found above versus below low-head dams. Some species (Mottled Sculpin, Longnose Dace, Logperch, Rock bass, and Rosyface Shiner) were only found below the low-head dams, but not above them, indicating that the dams were fragmenting the two streams being studied (Porto et al., 1999). A similar study on the Neosho River found more riffle species at sites downstream of two low-head dams, whereas fish typically found in more lentic habitats were found upstream of the dams (Gillette et al., 2005). In contrast to Porto et al. (1999) they did not find a decrease in species richness above the dams. Gillette et al. (2005) attributed this finding to the absence of migratory fishes in their region.

The focal point of this study was to assess the effect of a low-head dam on both environmental characteristics and biota on a fourth-order stream. Cullowhee Dam is a damaged, run-of-the-river dam built in 1930 by Biltmore Log Company to replace a failed dam that washed away in 1928 (McGill Associates, 2017). During high-flow periods, water diverts around the right side of the dam, causing erosion to the bank. Currently, Western Carolina University owns the dam. The primary purpose of this dam is to create a lentic environment to settle sediment prior to raw water intakes that are present upstream of the dam.

We conducted this study to provide a better understanding of how the dam may affect the aquatic macroinvertebrate and fish assemblages of the Tuckasegee River. The collected data serves as a baseline before action is taken to repair or remove the dam. We recorded and analyzed channel morphology, instream habitat, water velocity, benthic macroinvertebrates, and fish abundance & distribution above and below the dam.

STUDY AREA

The focal point of this study is Cullowhee Dam (Latitude 35°18’54.67”N, Longitude 83°10’33.35”W) located on the Tuckasegee River (Figure 1). The Tuckasegee River begins at the confluence of the East and West Fork Tuckasegee rivers. Both forks have large hydroelectric dams that influence the water quality of the mainstem Tuckasegee River. The Tuckasegee River is eventually joined by the Oconaluftee River near Bryson City, NC, and flows into Fontana Lake as a tributary to the Little Tennessee River.

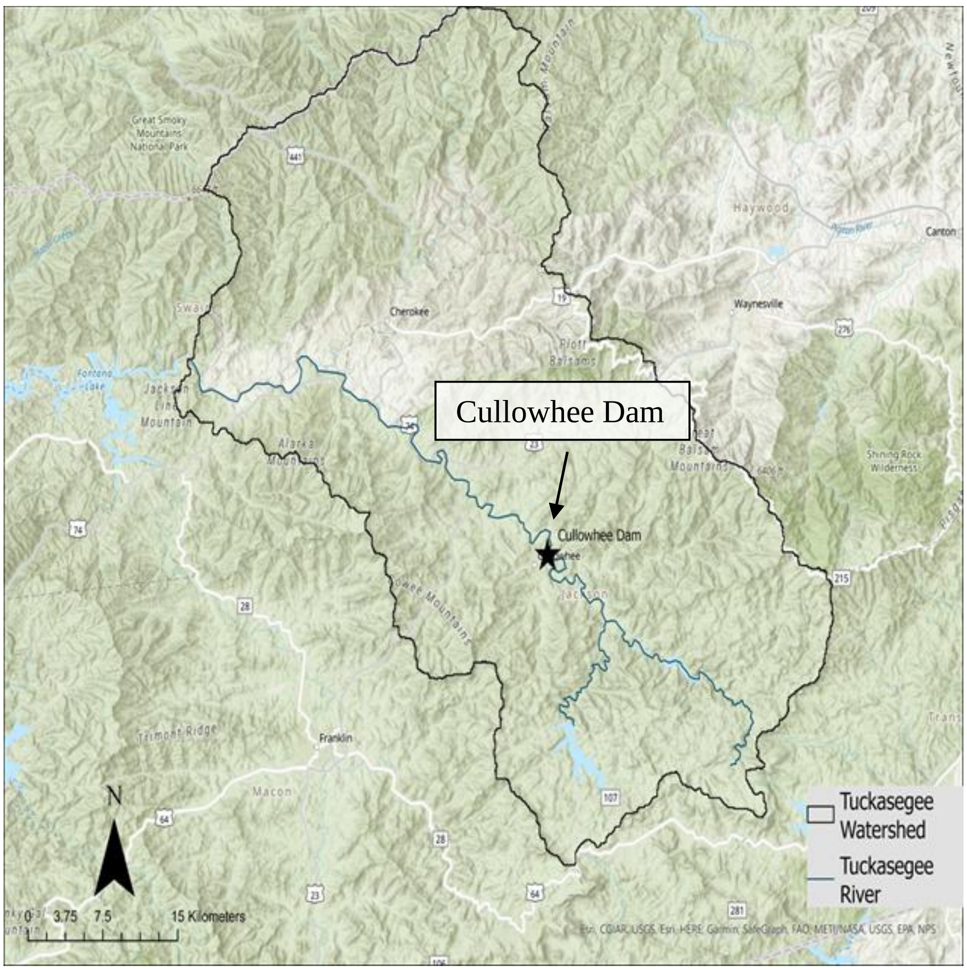

Figure 1. Cullowhee Dam is located on the Tuckasegee river, which is East of Western Carolina University in Cullowhee, NC.

The Tuckasegee River subbasin (Figure 1) covers 1,901 km^2 and is 89% forested as of 2006 (NCDEQ 2012). Portions of the Tuckasegee River are within the Nantahala National Forest and Great Smoky Mountains National Park. This subbasin contains some of the most pristine high-quality waters in the state, with numerous trout streams. Water quality concerns of the Tuckasegee River subbasin include impacts from developments on steep slopes, agricultural runoff, stream bank erosion, limited riparian cover, and wastewater failures (NCDEQ 2012).

Cullowhee Dam (Figure 2) is approximately 2 meters tall and 50 meters wide (McGill Associates, 2017). This dam previously generated power and is currently a reservoir for Western Carolina University and Tuckasegee Water and Sewer Authority raw water intakes. The impoundment lowers water velocity, so sediment will settle before raw water intakes that are located above the dam (McGill Associates, 2017).

Figure 2. Cullowhee Dam 2023. The red oval indicates an area of the dam where water diverts around the dam during high-flow periods, undercutting the bank. Without repair, erosion will occur under the adjacent road.

METHODS

Habitat Sampling

We sampled the following sites below the dam: Immediately downstream, 0.5 rkm Below, 7.8 rkm Below, and 11 rkm Below. We sampled the following sites above the dam: 1.2 rkm Above, 2 rkm Above, 7.8 rkm Above, and 13 rkm Above. The sites immediately adjacent to the dam (1.2 rkm Above, 2 rkm Above, immediately downstream, and 0.5 rkm Below) served as the focal point to indicate the dam's effect, whereas the sites furthest from the dam served as reference sites (Figure 3, Table 1). We chose easily accessible sites approximately equal distances above and below the dam. Due to safety concerns, sampling could not occur immediately above the dam, and rather sampling occurred in the closest wadable areas above the dam.

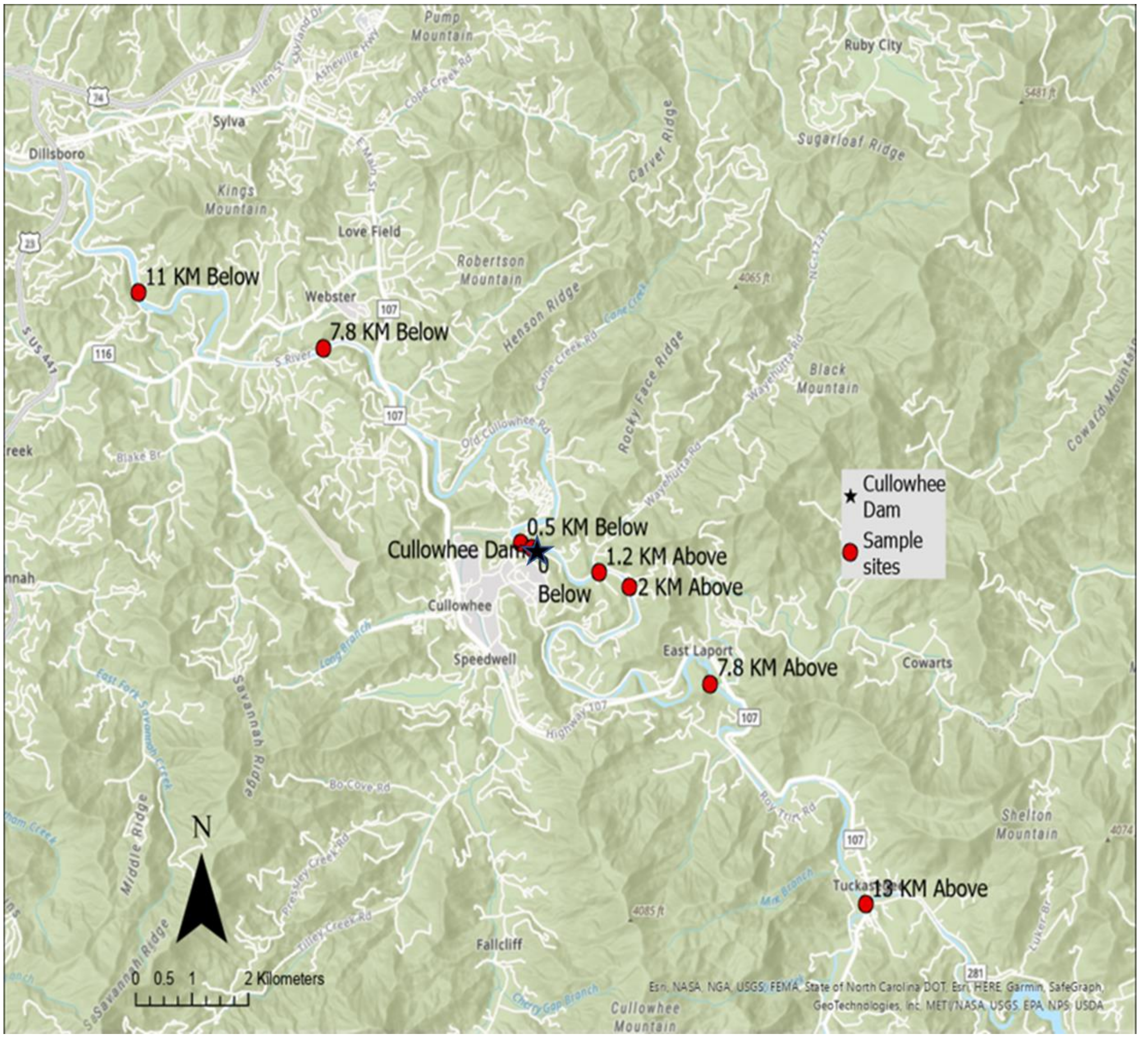

Figure 3. Location of habitat and macroinvertebrate sampling sites above and below Cullowhee dam located on the Tuckasegee river. A 200-meter reach was sampled within each site. The two pairs of the above and below dam sites adjacent to the dam served as main-effect sites, whereas the two pairs of the sites located furthest from the dam served as reference sites.

Table 1. Habitat and macroinvertebrate collection site locations both above and below the dam. Site type refers to whether the site was a reference or main-effect site. Location is the distance in river kilometers either above or below the dam.

Site type	Location
Reference	11 rkm Below (35.349687, -83.238993),
	7.8rkm Below (35.342207, -83.209522)
Main effect	Immediate Downstream (35.315354, -83.176306),
	0.5 rkm Below (35.318157, -83.178438)
Main effect	1.2 rkm Above (35.312154, -83.165621),
	2 rkm Above (35.308661, -83.160016)
Reference	7.8 rkm Above (35.29716, -83.147769)
	13 rkm Above (35.267814, -83.122992)

Each sample site was 200 meters long with 20 cross-section transects staked at ten-meter intervals (Figure 4). We measured the following characteristics within each transect at 1, 25, 50, 75, and 99% of the wetted width (Figure 4): water depth, column velocity, bottom velocity, wetted width, chain roughness, gradient, estimated percentages of dominant and subdominant substrate.

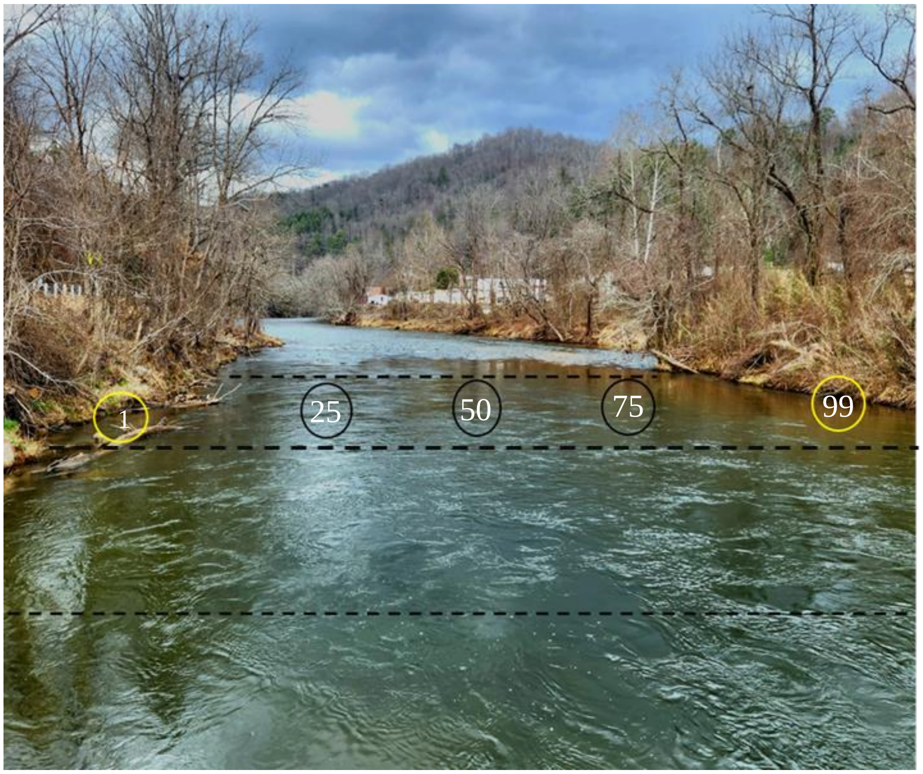

Figure 4. Example of two ten meter transects used for habitat sampling. The circles indicate the estimated stream width percentages found within each transect.

We measured channel morphology and environmental conditions within each 200-meter site to indicate the uniqueness between sites. We measured depth at the intervals listed above within each transect using a top setting wading rod. We measured bottom and column velocities with a transducer pointed upstream on a top-setting wading rod. We measured the column velocity at approximately 60% of the depth, while we measured the near bottom velocity at approximately 20% of the depth above the bottom of the riverbed. We allowed the readings on the meter to stabilize before the measurement was recorded (Gordon et al., 2006). We measured the wetted width within every transect by using a laser range finder and pointing it just above the water level at the opposite bank. We measured chain roughness (Saleh, 1993) with a 5-meter-long chain. Two individuals would drop the chain simultaneously and measured the shortened distance above the water's surface. We repeated this procedure ten times in both fast and slow-moving areas within each 200-meter site. We averaged the data from the 10 measures. Shorter chain lengths indicated greater amounts of course substrate on the riverbed. We placed a survey level at the first transect to measure the river gradient. A surveyor held a surveying rod plumb just above the water surface and recorded the measurement at each transect. I subtracted these two values from each other and divided by 20,000 cm (the 200-meter study reach converted to cm) to calculate the grade of the riverbed. The surveyors visually estimated the dominant and subdominant substrate percentages within approximately a 1 m^2 area at each stream width interval within each transect. We determined substrate classification based on a modified version of the Udden-Wentworth scale (Table 2). We recorded and averaged the dominant and subdominant substrate to create unique substrate percentages for each site.

Table 2. Modified version of the Udden-Wentworth grain scale used to measure the substrate size within each transect.

Size	Class
> 1500 mm	Bedrock
201 – 1500 mm	Boulder
81 – 200 mm	Cobble
4 – 80 mm	Gravel
1-3 mm	Sand
< 0.1 mm	Silt

Macroinvertebrate sampling

The sites for macroinvertebrate sampling remained the same as the habitat sampling listed above (Table 1, Figure 3). We sampled benthic macroinvertebrates in appropriate habitats within each 200-meter reach from June through August of 2021 and 2022. We sampled the main-effect sites above and below the dam at least once in 2021 and were followed by at least one additional sample in 2022. We sampled the reference sites once either in 2021 or 2022. We chose this period to allow for species variation throughout the summer months and temperature, water depth, and velocity changes.

Mid-channel sampling

We collected benthic macroinvertebrates using a modified version of the one-person kick net method as used by the U.S. Geological Survey for their National Water-Quality Assessment Program (NAWQA; Cuffney et al., 1993). We used a 1 meter wide, 500-μm mesh kick net to sample riffles within each site. We disturbed the substrate upstream of the kick net for approximately 60 seconds and repeated this process a maximum of four times or until we collected approximately 200 macroinvertebrates.

Shoreline sampling

We used two D-frame nets with 500-μm mesh for 2 minutes in a multi-habitat collection technique. This technique involved disturbing undercut banks, woody debris, or any other shoreline substrate to maximize the diversity of collected macroinvertebrates. We preserved the various substrates, such as leaves, sediment, wood debris, etc., in a plastic bag filled with 70% ethanol. We placed the sample in a plastic tray in the lab for sorting. We added ethanol to the sample when needed to prevent substate drying. We used a microscope and forceps to sift through the samples and remove any macroinvertebrates present. We analyzed each tray at least two times to minimize the number of overlooked macroinvertebrates.

Fish Sampling

We sampled fish from June through August 2021 in 100–200-m reaches centered upstream and downstream of the dam (Figure 5). We used two backpack electro fishers with three netters and covered as many habitats as possible within each study site, including riffles, runs, and pools (Temple et al., 2007; AFSSD, 1992). Backpack electrofishing proceeded upstream in faster-moving water. We created lanes with block nets in slower-moving water. Electrofishers shocked down to a single block net within each lane in these slower-moving areas.

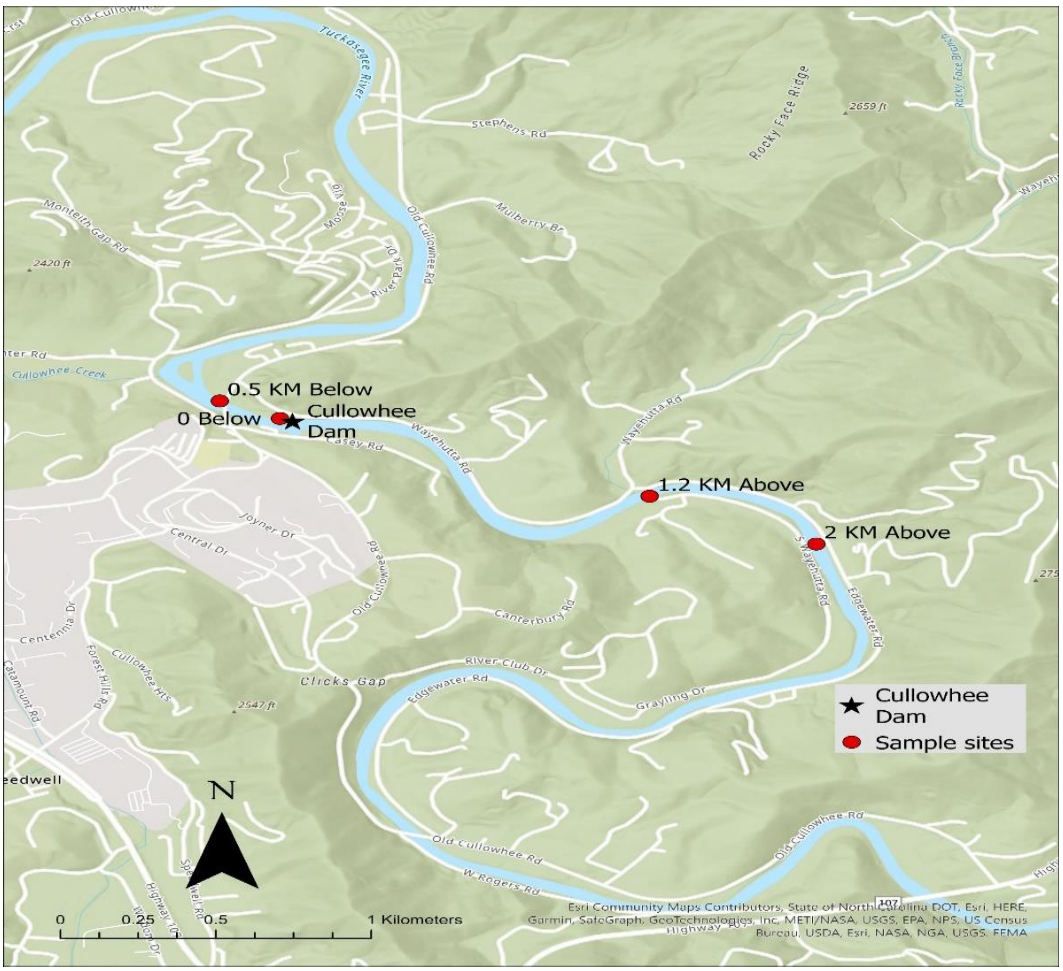

Figure 5. Electrofishing sample sites located above and below the Cullowhee Dam on the Tuckasegee River.

I used Merritt & Cummins (2008) to identify macroinvertebrate specimens to genus. I identified fish to species using Peterson Field Guide to Freshwater Fishes 2nd edition (Page & Burr, 2011), or Fishes of Tennessee (Etnier & Starnes, 2001).

STATISTICAL ANALYSIS

Habitat data

We performed most data analyses using PRIMER 7 (Quest Research Limited, Aukland, New Zealand). We calculated the average depth, bottom velocity, and column velocity using Microsoft Excel (Redmond, WA). We calculated the average of these variables at 1 and 99% stream width intervals for the shoreline sections, whereas we used the 25,50, and 75% stream width intervals to calculate the mid-channel habitat. In addition, we calculated the weighted percentages of the dominant and subdominant substrate at each site using the noted intervals above, depending on sample type. We transformed all habitat data to create a normalized distribution by subtracting the mean from each variable and dividing by the standard deviation (Clarke & Gorley, 2006). We performed a Principal Components Analysis to reduce the dimensionality of the data and to identify any patterns between habitat variables and the sample sites. We performed an Analysis of Similarities test (ANOSIM) using the resemblance matrix based on the Euclidean distance. The ANOSIM test is a computer-intensive way to determine if there are significant differences in variables by running many permutations that assume the null hypothesis is true and comparing observed data to these permutations. We conducted a one-way Analysis of Similarities Percentage (SIMPER) to identify which variables contributed the most to ANOSIM differences. This analysis helps determine the key factors driving the dissimilarity between samples. We created mean plots using Microsoft Excel to visualize the differences in habitat variables among factors. These plots provided a visual representation of the variation in the habitat variables across different factors, aiding in the interpretation of the data.

Fish and Macroinvertebrates

We transformed macroinvertebrate and fish data using a fourth-root transformation. This transformation helps to down-weight the contribution of highly abundant individuals and provides a better representation of rare species. Subsequently, using PRIMER 7, we created a resemblance matrix using Bray-Curtis similarity, which quantifies the similarity between samples based on their species composition. We employed non-metric multi-dimensional scaling (nMDS) with a target stress value below 0.1 to reduce the dimensionality of the data. This technique allows us to create a two-dimensional visual representation of the data and helps identify any patterns or clustering that may indicate differences in the communities present. (Clarke & Gorley, 2006). We conducted a one-way ANOSIM to assess for significant differences among factors. In this analysis, we used either two or four factors to evaluate differences in assemblages. The ANOSIM test helps determine whether the dissimilarity between the groups is greater than the dissimilarity within the groups, indicating significant differences in community composition. When two factors were tested, the terms "above" and "below" the dam were used. In this context, "above" refers to the sites located upstream of the dam, while "below" refers to the sites located downstream of the dam.

When four factors were tested, the following terms were used to represent different site locations relative to the dam:

- "Extreme below": Represents the sites furthest downstream of the dam.
- "Center below": Represents the downstream sites closest to the dam.
- "Center above": Represents the upstream sites closest to the dam.

- "Extreme above": Represents the upstream sites furthest from the dam.

We analyzed the species contributions per factor by using one-way similarity percentages with the Bray-Curtis similarity resemblance matrix.

RESULTS

Habitat Data Analysis

Complete habitat (Mid-channel and shoreline habitat)

After examining the PCA for the four-factor test, it was determined that the site located 13 km above the dam was an outlier since habitat variables such as the bottom velocity, column velocity, gravel percentage, wetted width, and gradient appeared much different than other reference sites (Table 3, Figure 6). At the 13 km above site, we observed an average column velocity and bottom velocity almost double the average of the remaining sites. We observed a much higher gravel percentage at 13 km above the dam site. We observed an average wetted width approximately seven times greater at the remaining sites versus the 13 km above the dam site. We recorded a slightly negative gradient at the 13 km above site, likely due to measurement errors, so we changed the gradient to approximately zero.

Table 3. Habitat data from the 13 km above dam site to the other sites. An average of the bottom velocity (BV), column velocity (CV), gravel percentage, wetted width, and the stream bed gradient was created for all sites excluding the 13 km above site for comparison.

	Avg. BV (m/s)	Avg. CV (m/s)	Gravel %	Avg. Wetted Width (m)	Gradient
13 km Above	0.31	0.58	43.1	6.2	≈ 0
Other sites	0.15	0.31	16.3	44.0	0.0002

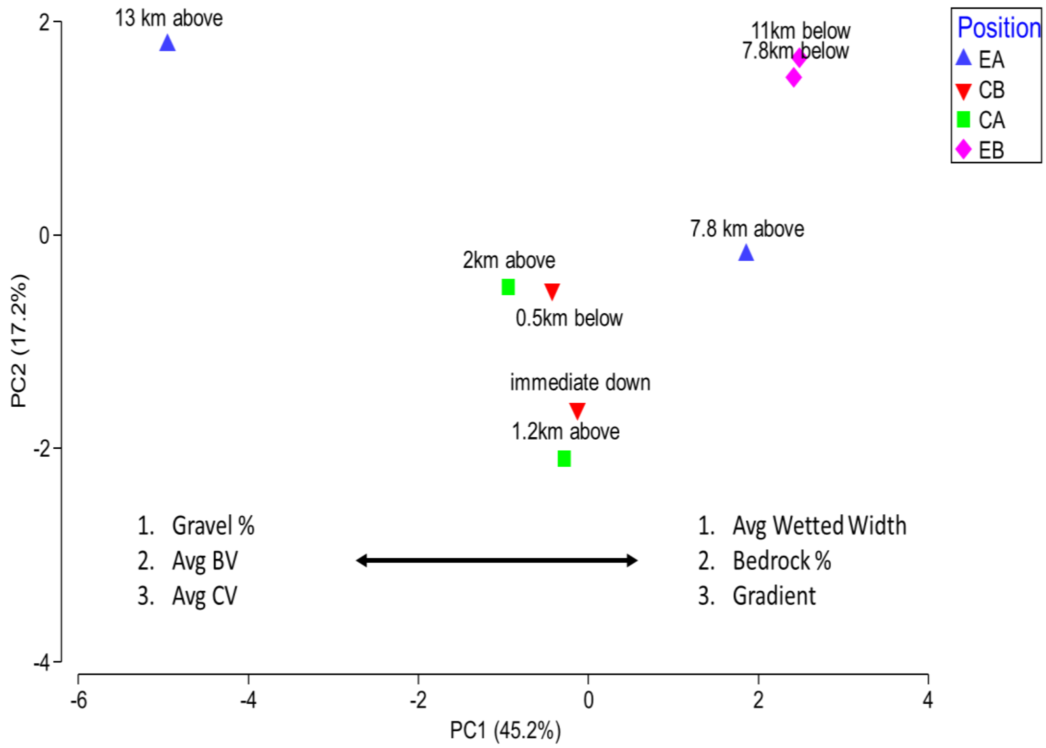

Figure 6. Principal Components Analysis of habitat within each 200-meter sample site. Each point represents a single sample occasion. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam. Principal Component 1 explained 45.2% of the habitat variation seen among sites. Gravel percentage, Average Bottom Velocity (Avg Bv), and Average Column velocity (Avg CV) was positively correleated (cutoff of 1). Average Wetted Width (m), Bedrock Percentage, and River Gradient influenced PC1 > 0. PC2 accounted for 17.2% of the habitat variation.

After removing the 13 km above site, PC1 explained 36.8% of the variation among the remaining sites. The main-effect sites were correlated with gravel percentage, cobble percentage, and column velocity (Figure 7). The average of each of these variables was higher at main effect sites than reference sites when we removed the 13 km above site from the analysis. In comparison, the remaining reference sites had higher bedrock percentages, greater wetted width at the reference sites, and greater gradient at the reference sites below the dam.

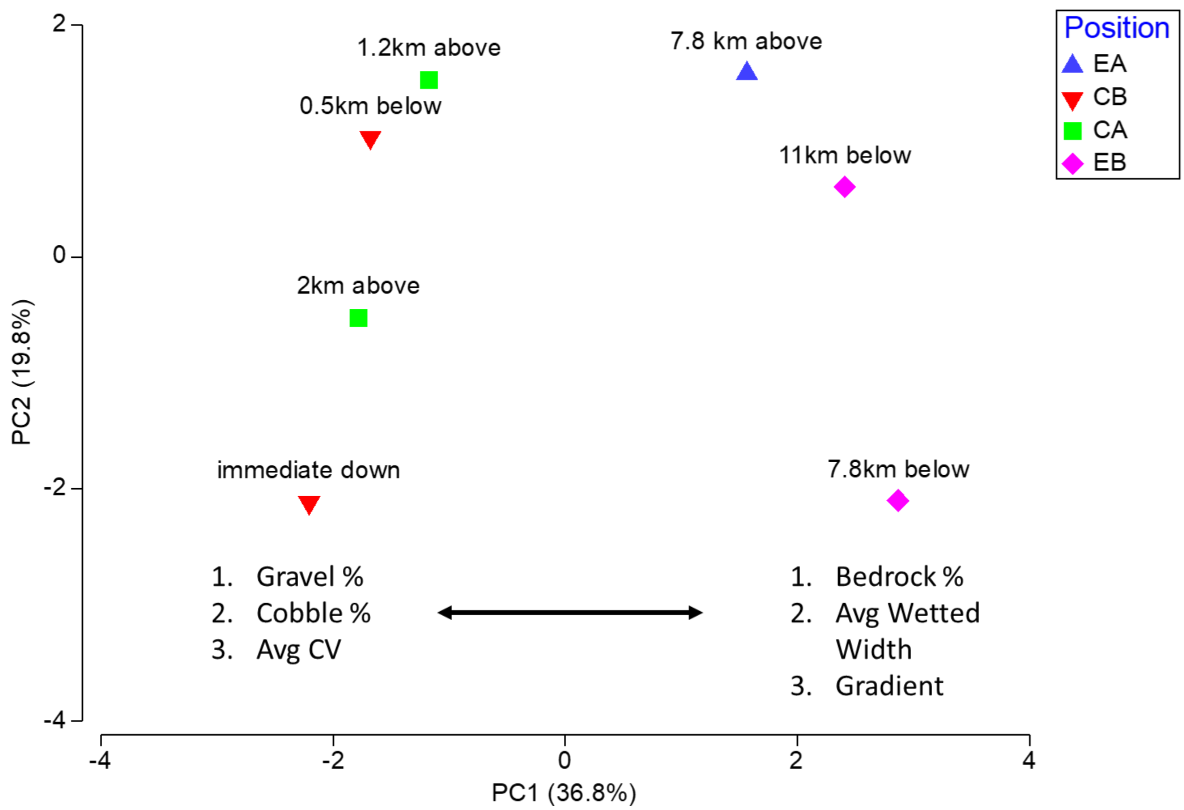

Figure 7. Principal Components Analysis of habitat within each 200-meter sample site excluding the 13 km Above site. Each point represents a single sample occasion. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam. Principal Component 1 displayed 36.8% of the habitat variation seen among sites. Gravel percentage, Cobble percentage, and Average Column velocity influenced PC1 < 0 whereas the Average Wetted Width (m), Bedrock Percentage, and River Gradient influenced PC1 > 0. PC2 accounted for 19.8% of the habitat variation.

The average column velocity was lowest at the uppermost reference site (7.8 km above). The column velocity increased from the below dam reference sites to similar levels immediately above and below the dam. The column velocity at the downstream reference sites decreased to similar levels as the above dam reference site (Figure). Bedrock was virtually nonexistent at main-effect sites centered around the dam. In comparison, the reference site bedrock percentage varied from 25-40% (Figure). Cobble percentage was greatest at sites above the dam. Average cobble percentage decreased slightly below the dam, with a drastic decrease at the reference sites downstream of the dam (Figure). There was an increase in the average gravel percentage at the main-effect sites located below the dam, with a drop in the gravel percentage at the reference sites below the dam (Figure). Gravel percentage was similar at all above dam sites. The wetted width was similar between all the above dam sites and the main-effect sites below the dam. There was a sharp increase in the wetted width at the reference sites located below the dam (Figure). The average depth was greatest at the sites located immediately below the dam, whereas other sites had a similar average depth (Table 4). The average bottom velocity was similar at all sites. However, there was a slight increase in the bottom velocity at the site 0.5 km below the dam (Table 4). Boulder percentage was similar among all sites with a slight increase in boulder percentage at the main-effect sites below the dam (Table 4). Percentage of sand was lowest at the upstream reference site. The sand percentage was greatest at the main-effect sites above the dam, with similar sand percentages at both downstream main-effect and reference sites (Table 4). The silt percentages were similar at all sites, with a slight increase in silt at the site 0.5 km below the dam (Table 4). There was an increase in the woody debris percentage at the main-effect sites immediately above the dam. In contrast, the woody-debris percentage was virtually nonexistent at other sites (Table 4). Chain roughness was similar at all the above dam sites and the below dam reference site. However, there was an increase in chain length at the main-effect sites below the dam, indicating that the substrate was likely smaller below the dam than above the dam (Table 4).

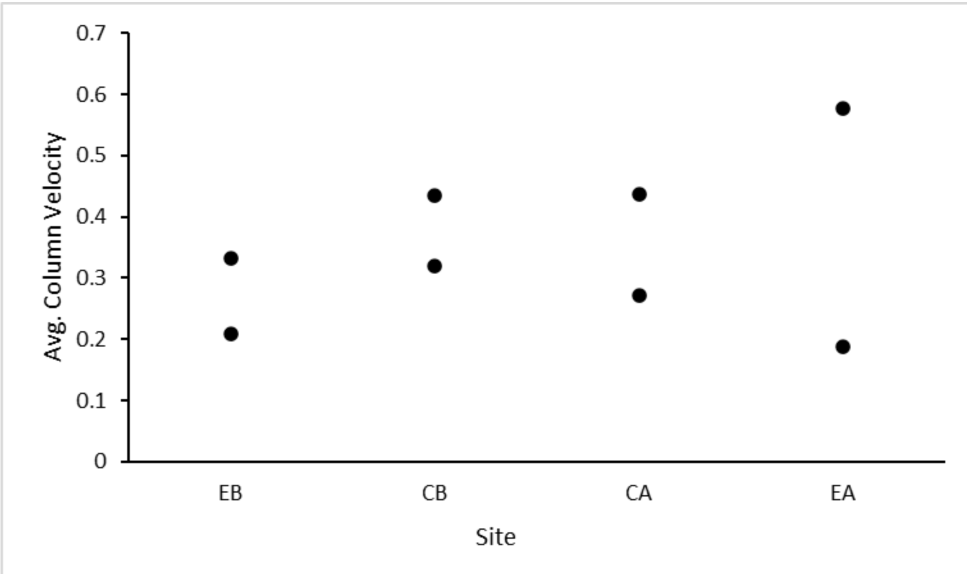

Figure 8. Average column velocity of each 200-meter site. Each data point represents one sample occurrence. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

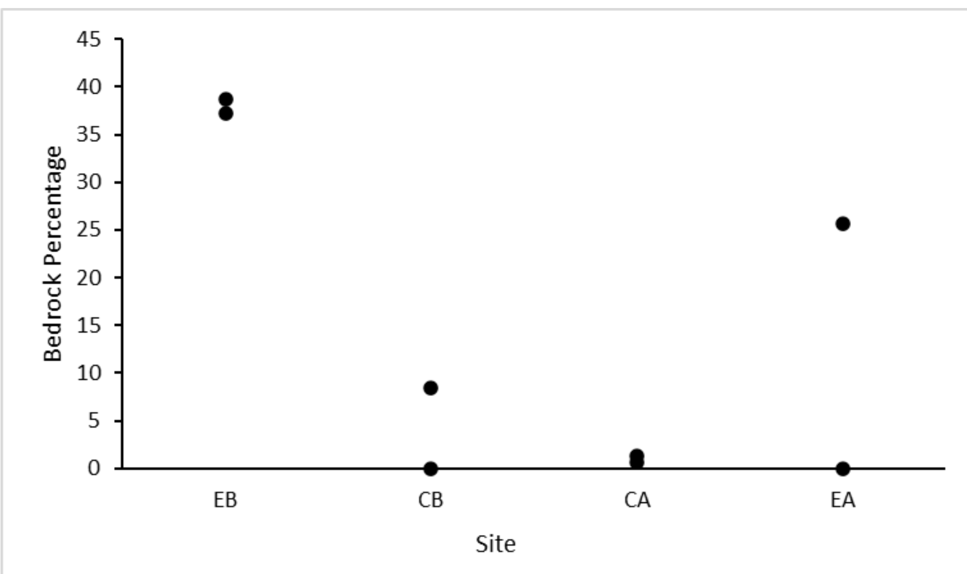

Figure 9. Bedrock percentage within each 200-meter site. Each data point represents one sample occurrence. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

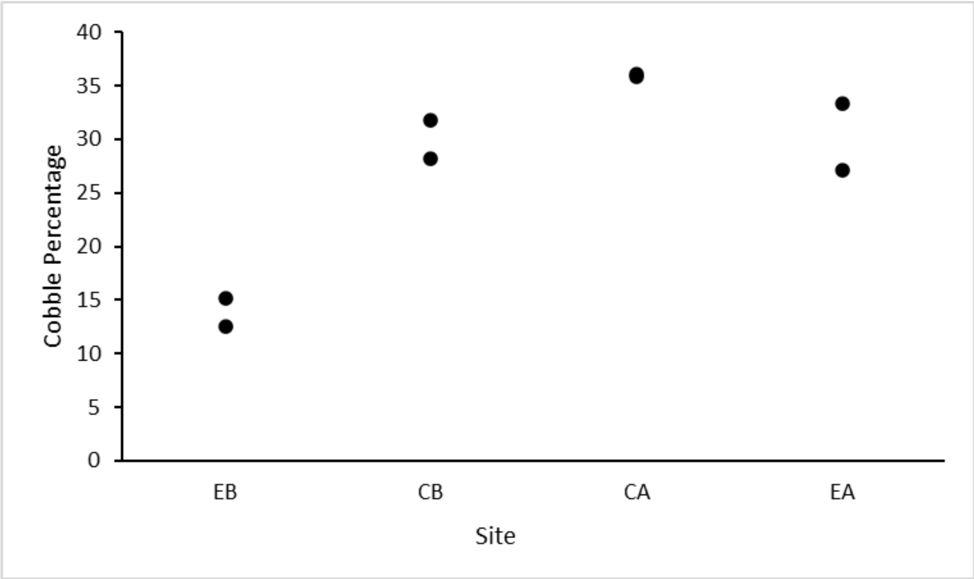

Figure 10. Cobble percentage within each 200-meter site. Each data point represents one sample occurrence. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

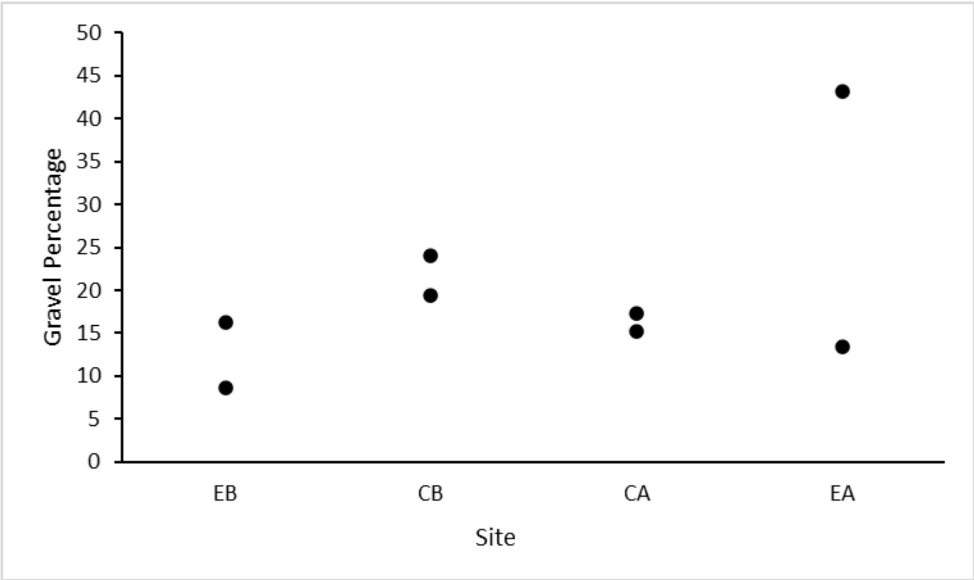

Figure 11. Gravel percentage within each 200-meter site. Each data point represents one sample occurrence. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

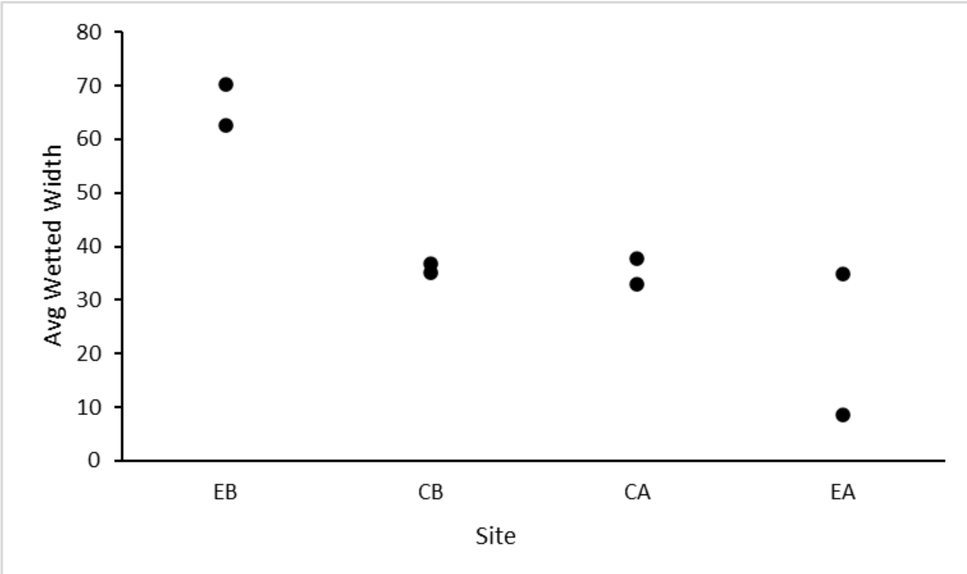

Figure 12. Average wetted width (m) within each 200-meter site. Each data point represents one sample occurrence. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

Table 4. Summary table of habitat variables from the combined habitat. Avg. BC = Average Bottom Velocity, Bdr per = boulder percentage, Snd per = sand percentage, Slt per = silt percentage, wd per = woody debris percentage, Chain Ro= chain roughness. The range indicates the maximum and minimum amount for the indicated variable. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

	EB	CB	CA	EA
Avg. Depth (m)	0.45-0.50	0.58-0.66	0.42-0.54	0.34-0.44
Avg. BV (m/s)	0.12-0.14	0.14-0.25	0.13-0.21	0.10-0.31
Bdr per	10.10-15.40	11.60-18.50	10.30-17.30	1.30-12.30
Snd per	13.50-21.50	18.70-21.90	18.60-25.50	7.20-20.30
Slt per	1.80-5.70	2.40-10.50	2.00-6.50	2.00-8.50
Wd per	1.40-2.00	1.40-3.10	5.80-7.80	0-6.20
Chain Ro	4.29-4.40	4.38-4.44	4.27-4.36	4.32-4.51

Collectively, habitats within the main effect sites were significantly different ($R = 0.5$, $p = 0.01$) from reference sites when we included the 13 km above site. We did not observe a significant difference in the habitat when we grouped the main effect and reference sites above and below the dam ($R = 0.063$, $p = 0.25$). After the removal of the 13 km above site, the habitats of the reference sites became more similar to the habitats of the main-effect sites ($R = 0.704$, $p = 0.06$).

Mid-channel data

We collected mid-channel habitat data from riffles within the 25-75% stream width intervals (Table A2). We used a similarity percentages breakdown (SIMPER) to determine which habitat variables contributed most to the difference between above and below dam sites. The three measured characteristics that contributed most to the difference were the amount of cobble, average depth, and woody debris. These three variables account for approximately 36% of the variation in habitat characteristics above and below the dam. The sites located 1.2 to 2 km above the dam have the greatest cobble percentages, followed by similar percentages immediately below and furthest upstream from the dam (Figure 8). The sites located furthermost upstream of the dam contained the shallowest average depth. The depth increased as we moved closer to the dam, with the deepest sites being located immediately below the dam (Figure 9). The upstream sites located closest to the dam had the highest abundance of woody debris. Woody debris was virtually nonexistent at the other sites (Figure 10).

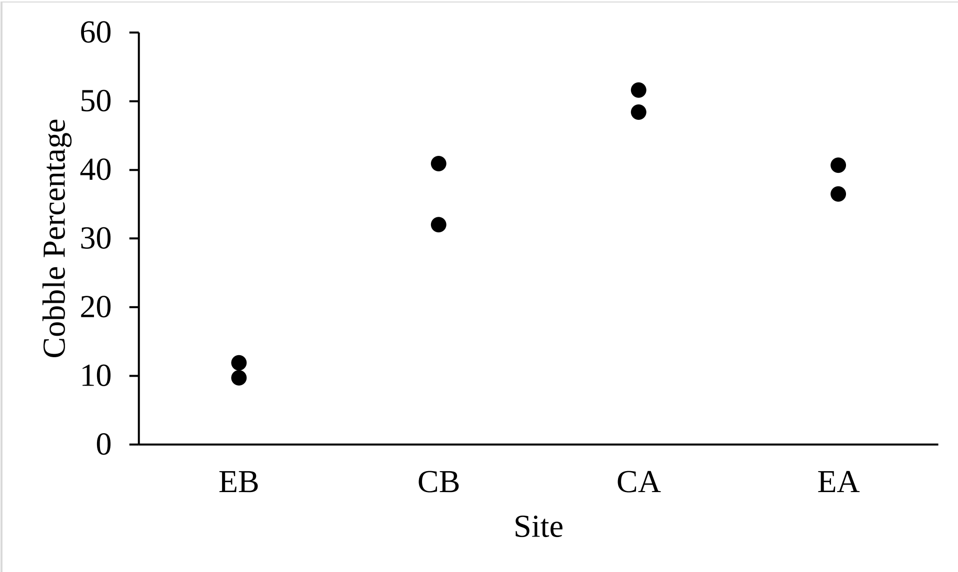

Figure 8. Estimated cobble percentages found in the mid-channel habitat within each 200-meter site. Each data point represents the average cobble percentage within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

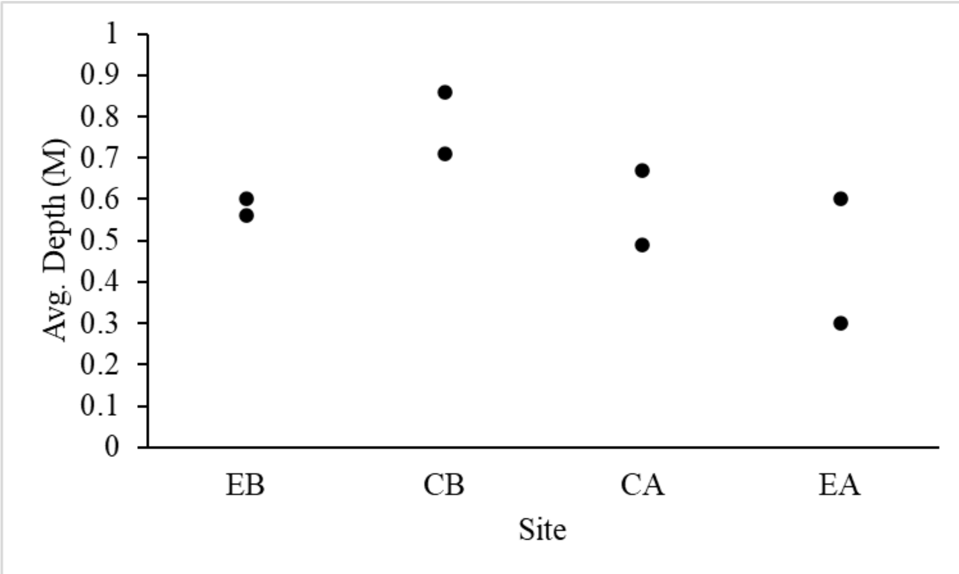

Figure 9. Average depth measured using a top-setting wading rod within the mid-channel habitat of each 200-meter site. Each data point represents the average depth within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

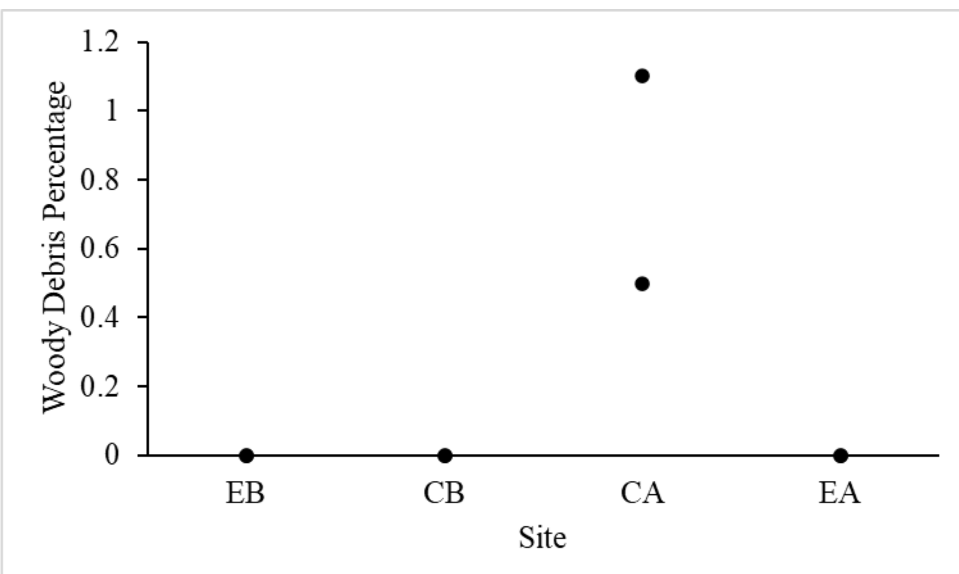

Figure 10. Average estimated woody debris percentage found within the mid-channel habitat of each 200-meter sample site. Each data point represents one sampling occasion. There were two sites per factor. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

PC1 of the mid-channel habitats PCA accounted for 39.2% of the variation in habitat variables (Figure 11). Bedrock, silt, and boulder percentages were correlated with all reference sites excluding the 13 km above reference site. The average column and bottom velocity in addition to the gravel percentage was correlated with all main-effect sites and the 13 km above reference site. After further review, bedrock percentages were highest at all reference sites excluding the 13 km above site (Figure 12). Overall, the average amount of silt was highest at reference sites versus main-effect sites (Figure 13). However, the silt percentages indicate that silt was virtually non-existent at mid-channel sites. Boulder percentage was similar at all sites (Figure 14). The average bottom velocity (Figure 15), column velocity (Figure 16), and gravel percentage (Figure 17) was highest at main-effect sites compared to the reference sites.

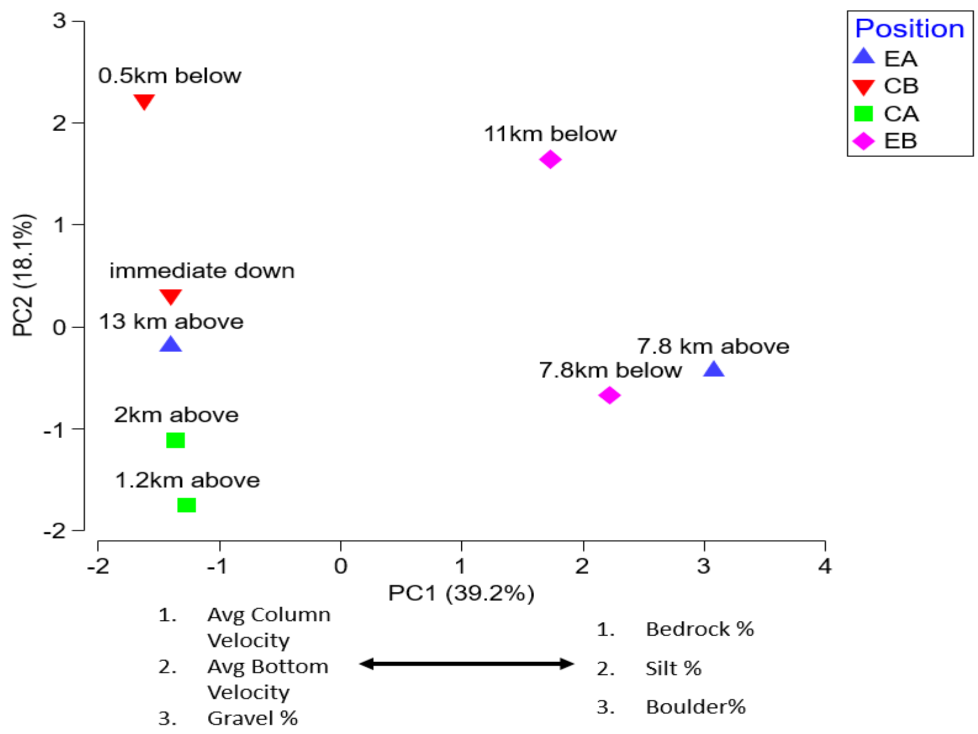

Figure 11. Principal Components analysis of the mid-channel habitat within each study site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam. Each distance associated with a data point was the distance in river kilometers from the dam.

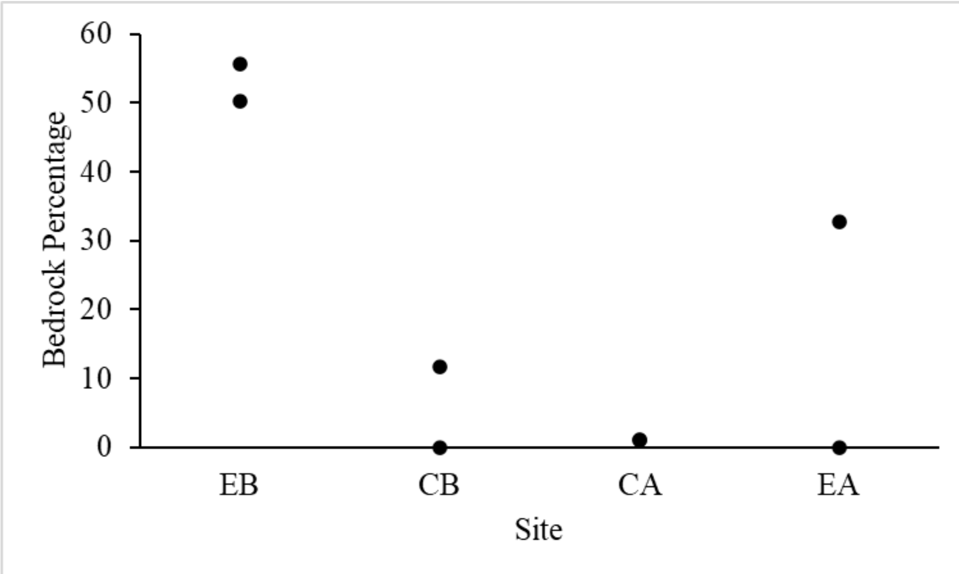

Figure 12. Means plot of bedrock percentage within the mid-channel habitats. Each data point represents the average bedrock percentage within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

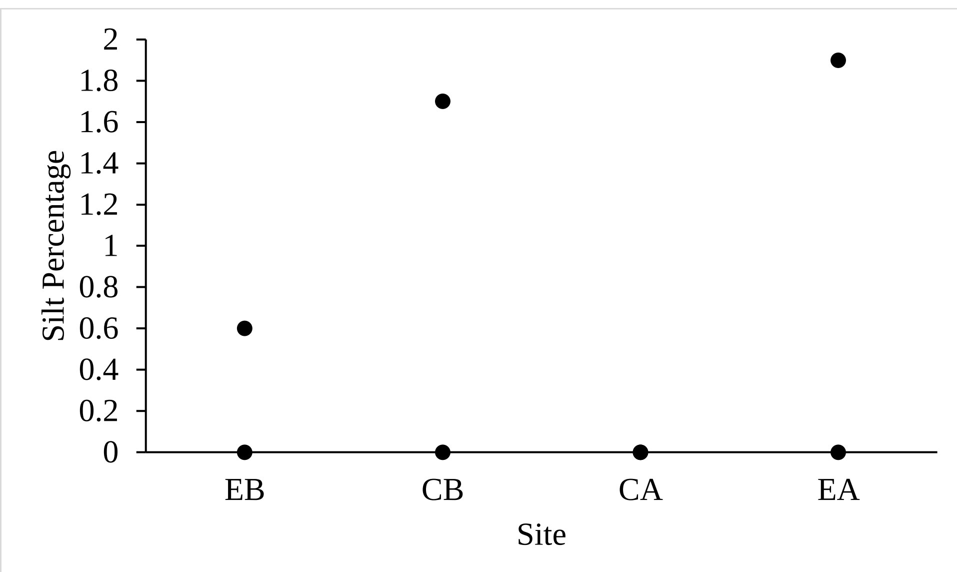

Figure 13. Means plot of silt percentages within the mid-channel habitats. Each data point represents the average depth within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

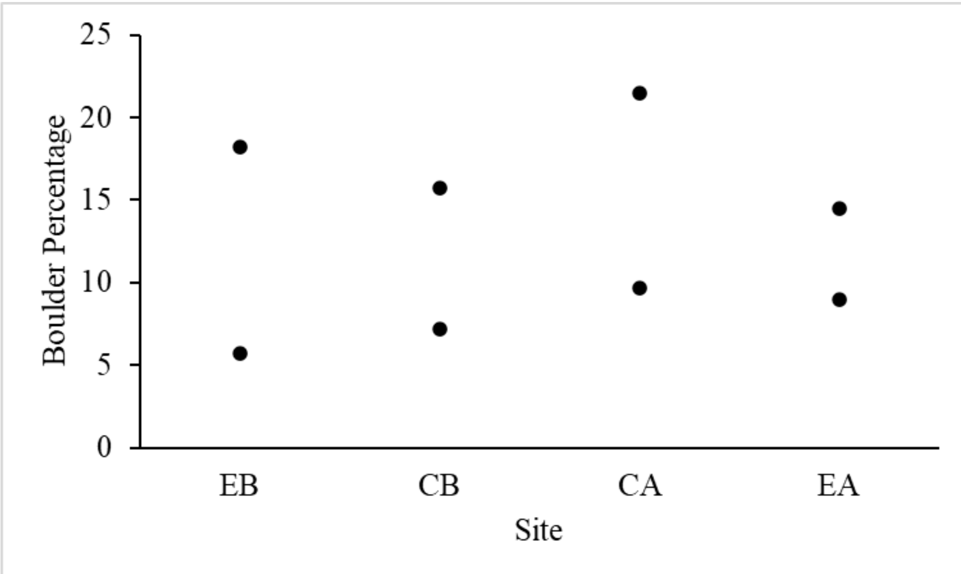

Figure 14. Means plot of the boulder percentage within the mid-channel habitats. Each data point represents the average depth within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

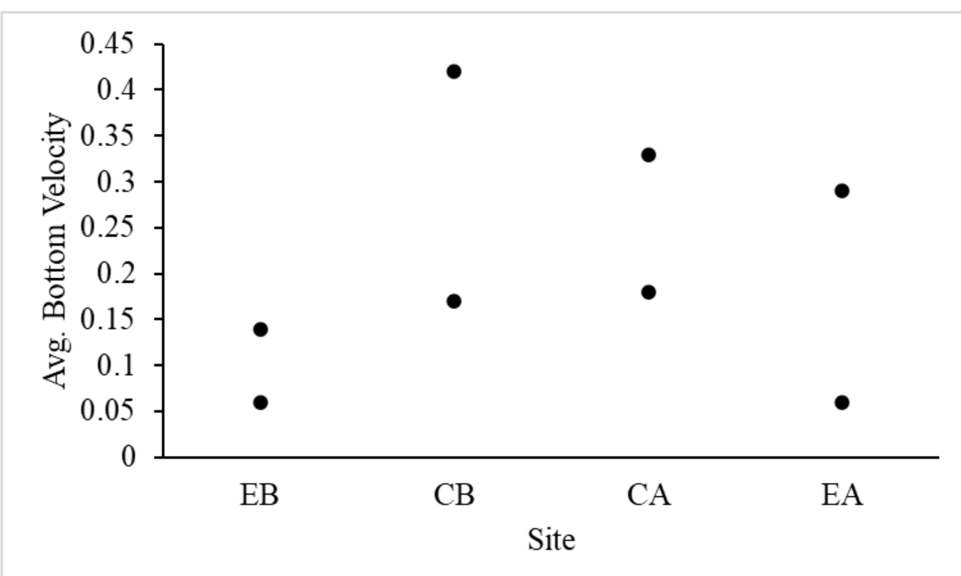

Figure 15. Means plot of the average bottom velocity of the mid-channel habitats. Each data point represents the average depth within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

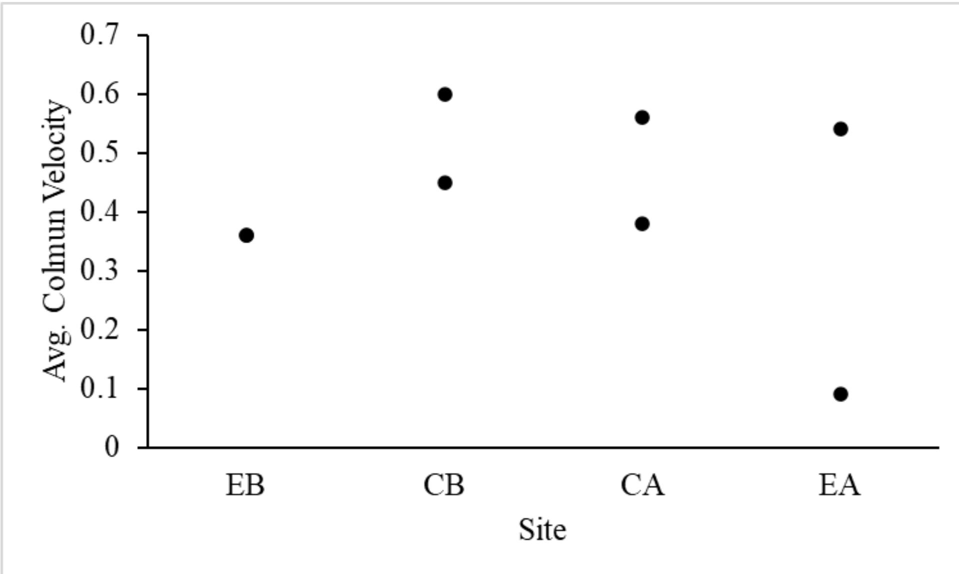

Figure 16. Means plot of the average column velocity of the mid-channel habitats. Each data point represents the average depth within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

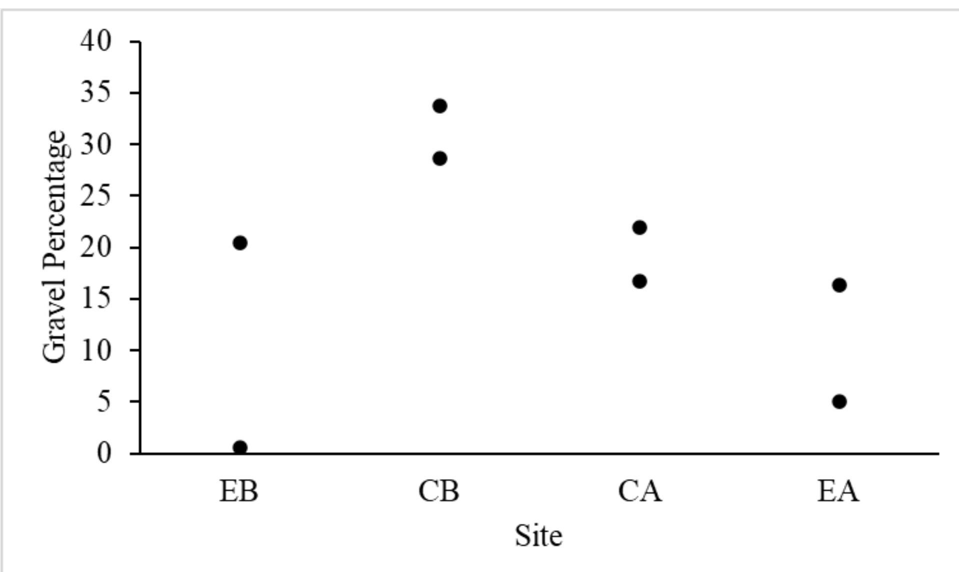

Figure 17. Means plot of the gravel percentage within mid-channel habitats. Each data point represents the average depth within the mid-channel habitat of a single site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

Both main-effect sites and reference sites from the mid-channel habitat were similar (R = 0.458, p = 0.09). The above and below dam mid-channel habitats were similar (R = 0.083, p = 0.2).

Shoreline habitat data

We collected shoreline habitat data from both main-effect and reference sites located above and below the dam (Table A3). We measured shoreline habitat characteristics within two meters of each transect's left and right banks. The multi-habitat macroinvertebrate sampling technique occurred in this area and allowed us to determine if differences in shoreline habitat exist among sites above and below the dam.

We used a Similarities Percentages Breakdown (SIMPER) analysis to rank the variability of habitat variables within the shoreline habitat. The boulder percentage (13.81%), average depth (11.92%), and woody debris percentage (11.18%) contributed to 37% of the overall variation observed above and below the dam. On average, the percent of the boulder substrate within the shoreline habitat was greater below the dam than above the dam (Figure 18). The sites located below the dam had a greater average depth than those above the dam. In addition, the sites located below the dam had a smaller depth variation than those sites above the dam (Figure 19). We observed a higher presence of woody debris above the dam compared to below it, with the highest percentages found immediately above the dam (Figure 20). The upstream sites closest to the dam tended to have more sand than the others (Figure 21).

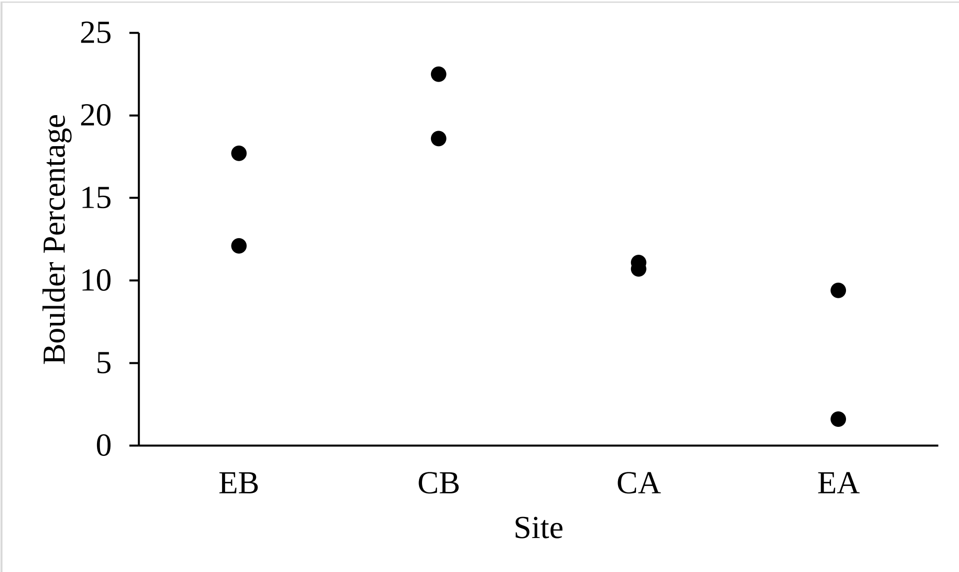

Figure 18. Average estimated shoreline (within 1 meter of the bank) boulder percentage within each 200-meter site. Each data point represents one sample site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

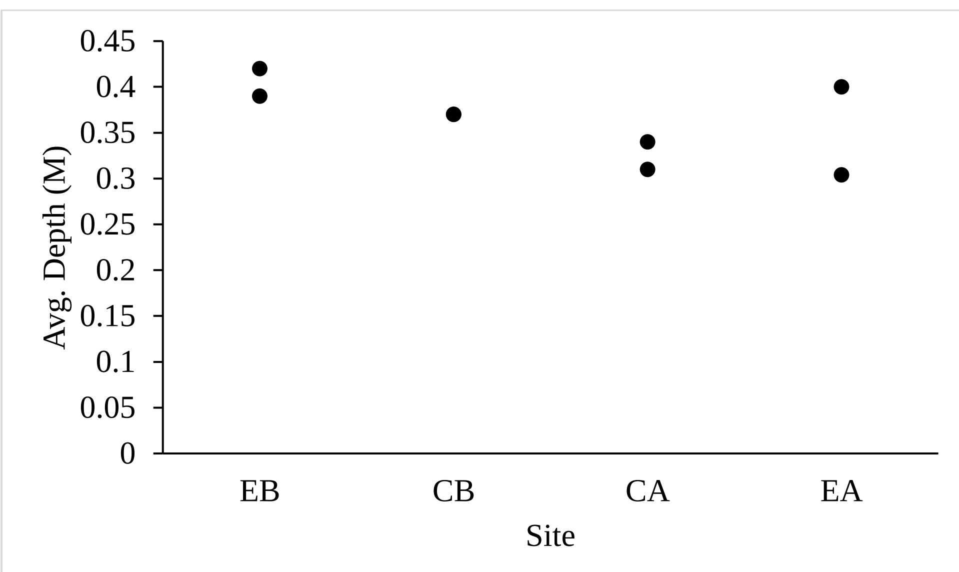

Figure 19. Average depth of shoreline habitat (within 1 meter of the bank) within a single site measured in meters using a topsetting wading rod. Each dot represents the average depth within a 200-meter site. The average depth for the CB sites were the same. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

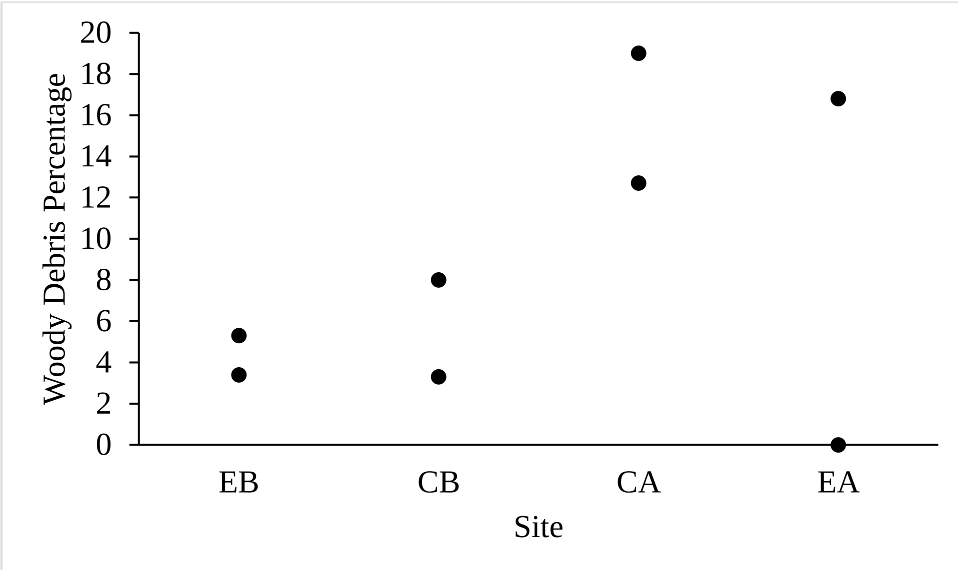

Figure 20. Shoreline (within 1 meter of the bank) woody debris percentage of reference sites and main-effect sites. Each data point represents the average woody debris percentage from one 200-meter site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam.

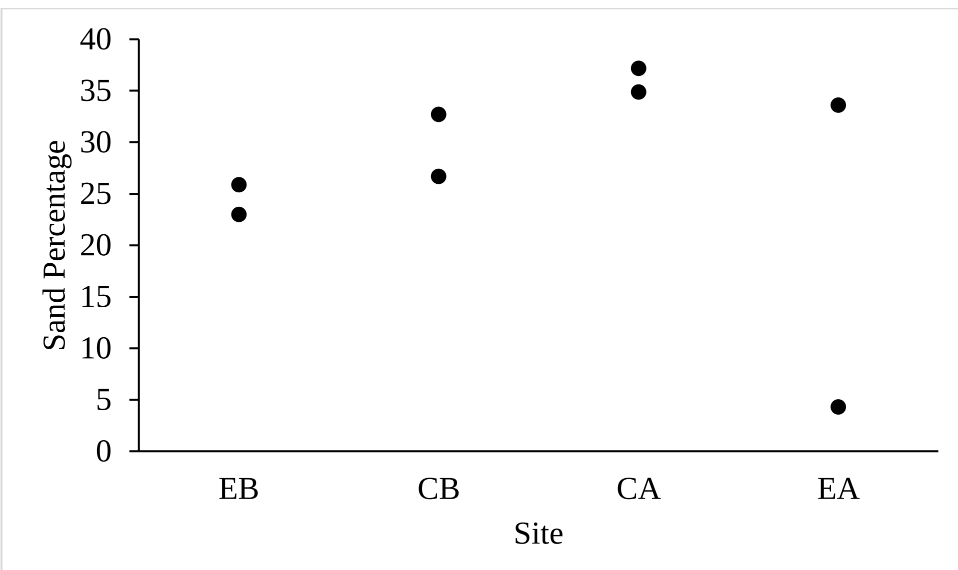

Figure 21. Shoreline (within 1 meter of the bank) sand percentage of reference sites and main-effect sites. Each data point represents the average sand percentage from one 200-meter site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam

PC1 of the four-factor PCA accounted for 36.8% of the shoreline habitat variation seen amongst sites, whereas PC2 accounted for 24.1% of the variation for a total of 60.9% of the cumulative variation (Figure 22). We observed no distinct grouping of reference sites or sites above and below the dam. There were no clear clusters or patterns that could differentiate the reference sites from those located above or below the dam. The woody debris percentage, sand percentage, and average bottom velocity best explain most sites through PC1. Woody debris was absent at the site located 7.8 km above the dam. This site also had a much lower sand and bottom velocity, which is why it was deemed to be an outlier compared to other sites. Overall, the shoreline habitat above and below the dam was similar (two-factor $R = 0.125$, $p = 0.229$: four-factor $R = 0.229$, $p = 0.152$).

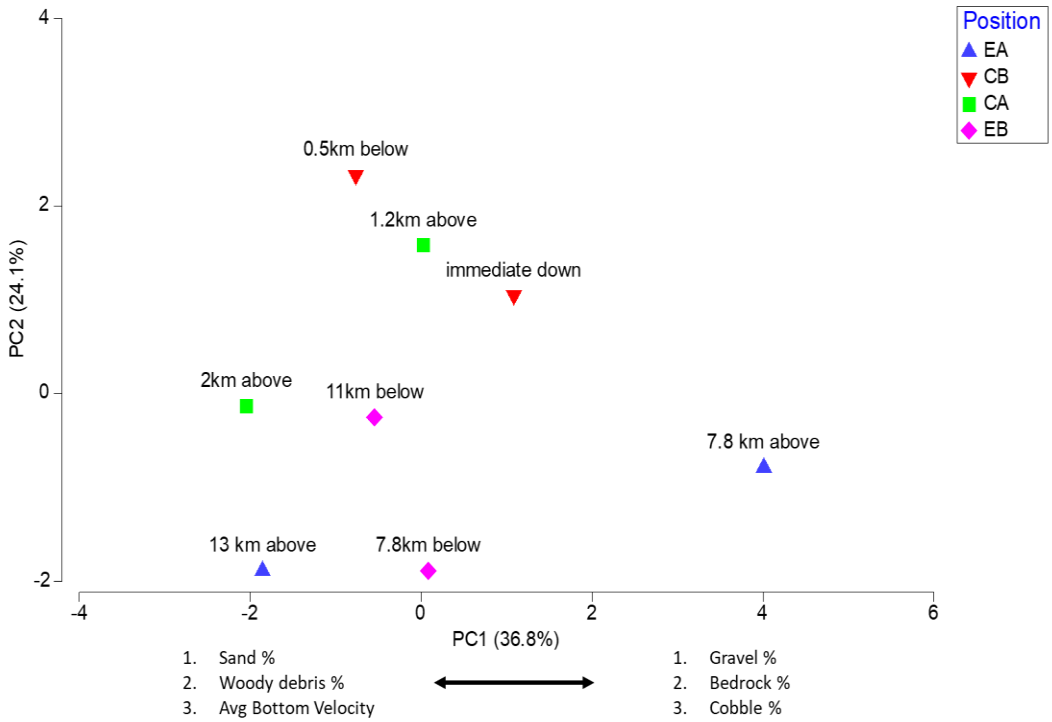

Figure 22. Principal Components analysis of the shoreline habitat (within 1 meter of the bank) within each study site. EB = extreme below & EA = extreme above are reference sites located furthest downstream and upstream of the dam. CB = center below & CA = center above representing the main-effect sites both above and below the dam. Each distance associated with a data point was the distance in river kilometers from the dam.

Macroinvertebrate Analysis

Mid-channel Sampling Results

We collected a total of 36 macroinvertebrate genera over 16 samplings (Table A4). We used a two-dimensional nMDS to visualize clustering among sites, indicating if differences among the indicated factors may be present. We observed no distinct grouping in the nMDS comparing reference sites to the main effect sites (Figure 23). A moderate stress level of 0.14 indicates that the true positions may be distorted and could influence the interpretation of the data. When considering only the above and below dam factors, we observed a similar random pattern. There was no discernible clustering or pattern that could differentiate between the sites above and below the dam ((stress = 0.14 (Figure 24)).

We detected no difference using the analysis of similarities test (R = 0.036, p = 0.37) between macroinvertebrate assemblages when comparing the reference sites and the main effect sites above and below the dam against each other. The macroinvertebrate communities above the dam were similar to the communities below the dam (R = 0.001, p = 0.43). EPT percentages did not vary significantly between reference and main-effect sites (R = -0.087, p = 0.76). Macroinvertebrate communities above and below the dam and between reference and main-effect sites contained sufficient species overlap, so we did not detect a significant difference between communities.

While there was no statistically significant difference between macroinvertebrate communities, the average macroinvertebrates' species richness and Shannon Diversity index values were higher above the dam than below the dam (Table 5, Figure 25, Figure 26). We observed higher species richness and Shannon Diversity index at main-effect sites compared to references sites; however, these values did not vary significantly (Figure 27 & Figure 28). Therefore, we concluded that the dam is likely not a barrier to movement upstream or downstream of insect macroinvertebrates since the main effect sites have a higher species richness and Shannon Diversity index than the reference sites.

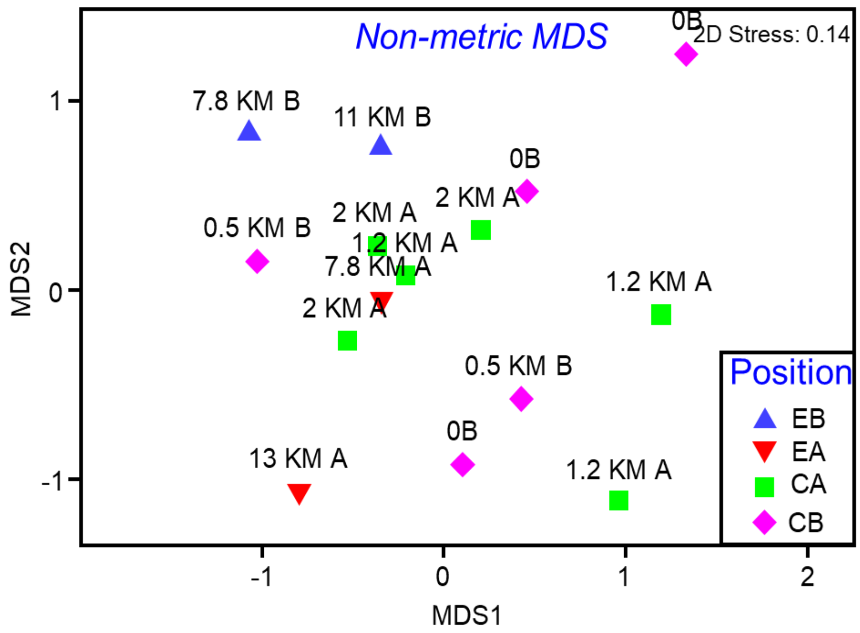

Figure 23. Non-metric multi-dimensional scaling (target stress < 0.1) of macroinvertebrate communities within the mid-channel habitat using 4 factors to compare above and below dam reference sites (EA = Extreme Above, EB = Extreme Below) against above and below dam main-effect sites (CB = Center Below, CA = Center Above). The mid-channel macroinvertebrates were collected using a fine mesh kick seine where the substrate was disturbed for 60 seconds up to four times or until approximately 200 macroinvertebrates were collected.

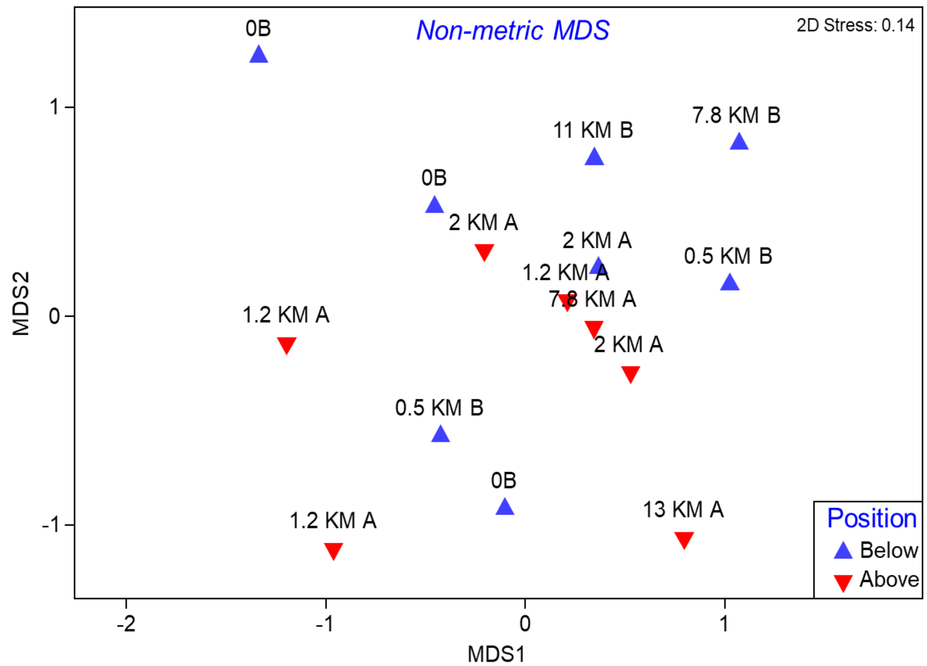

Figure 24. Non-metric multi-dimensional scaling (target stress < 0.1) of macroinvertebrate communities within the mid-channel habitat using two factors to compare the above and below dam sites. The mid-channel macroinvertebrates were collected using a fine mesh kick seine where the substrate was disturbed for 60 seconds up to four times or until approximately 200 macroinvertebrates were collected.

Table 5. Diversity of macroinvertebrates collected from the mid-channel habitat. "Sample" represents the location in river kilometers of the site located above or below the dam. S = Species Richness, N = number of individuals, H' = Shannon Diversity index. Any entries containing a range indicates more than one sampling occurrence.

Sample	S	N	H'(ln ())
13 rkm A	14	138	1.9
7.8 rkm A	19	203	2.6
2 rkm A	17-20	193-198	2.4-2.6
1.2 rkm A	15-19	173-197	2.3-2.5
0 rkm B	15-17	146-185	2.1-2.4
0.5 rkm B	15-19	198-204	2.0-2.2
7.8 rkm B	11	192	1.9
11 rkm B	21	164	2.5

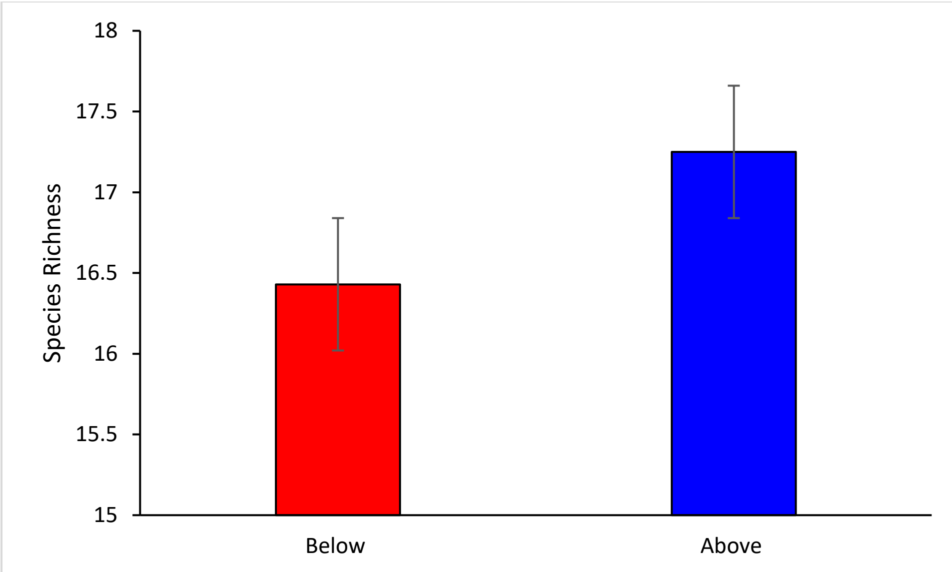

Figure 25. Average species richness (+/- standard error) of benthic macroinvertebrates collected from the mid-channel habitat both above and below the dam. The averages were based upon 1492 macroinvertebrates identified to genera above the dam and 1262 macroinvertebrates below the dam.

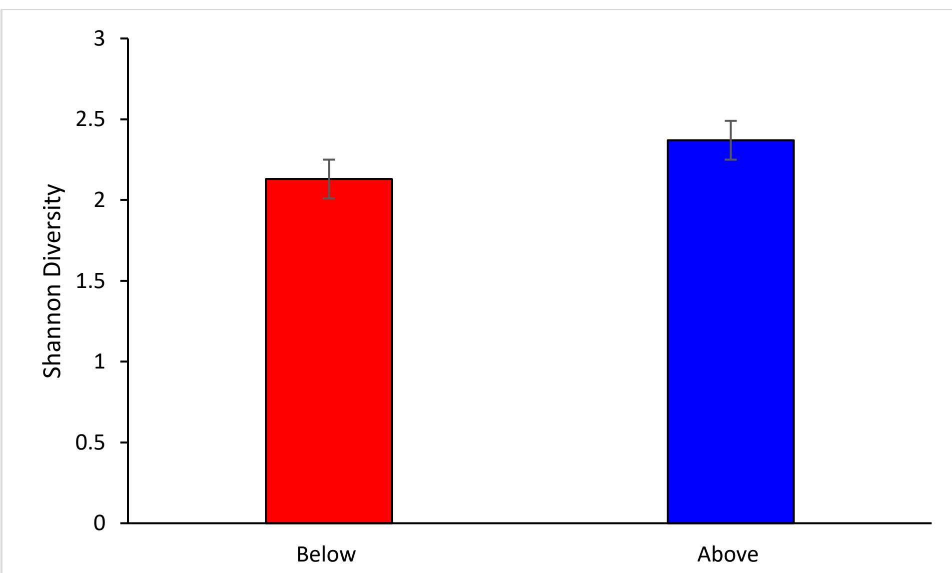

Figure 26. Average Shannon Diversity (+/- standard error) of benthic macroinvertebrate communities collected from the mid-channel habitat both above and below the dam. The averages were based upon 1492 macroinvertebrates identified to genera above the dam and 1262 macroinvertebrates below the dam.

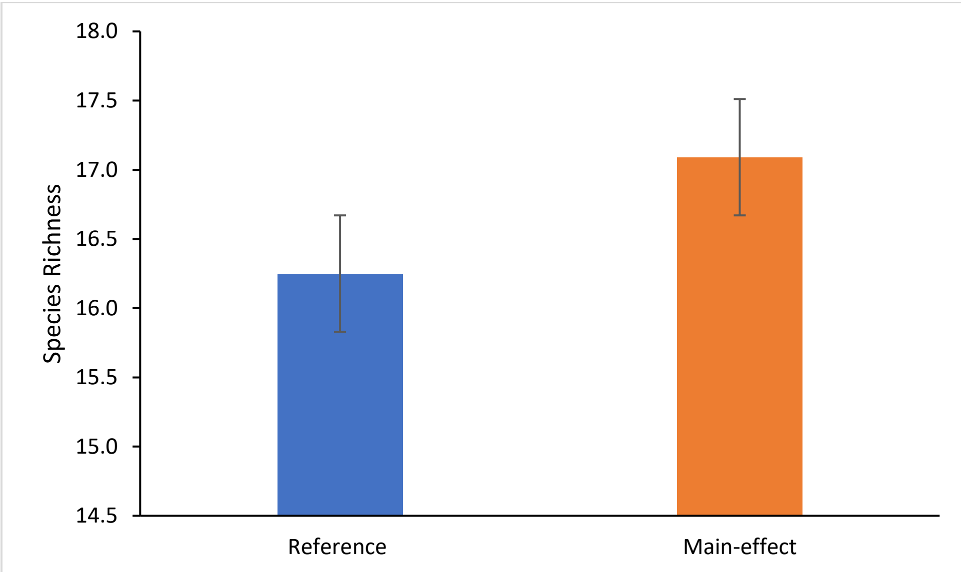

Figure 27. Average species richness (+/- standard error) of benthic macroinvertebrates collected from the mid-channel habitat both reference sites and main-effect sites. Reference sites are located 7.8 to 13 rkm above and below the dam, while the main-effect sites are located immediately below the dam to 0.5 km below the dam and 1.2 to 2 rkm above the dam.

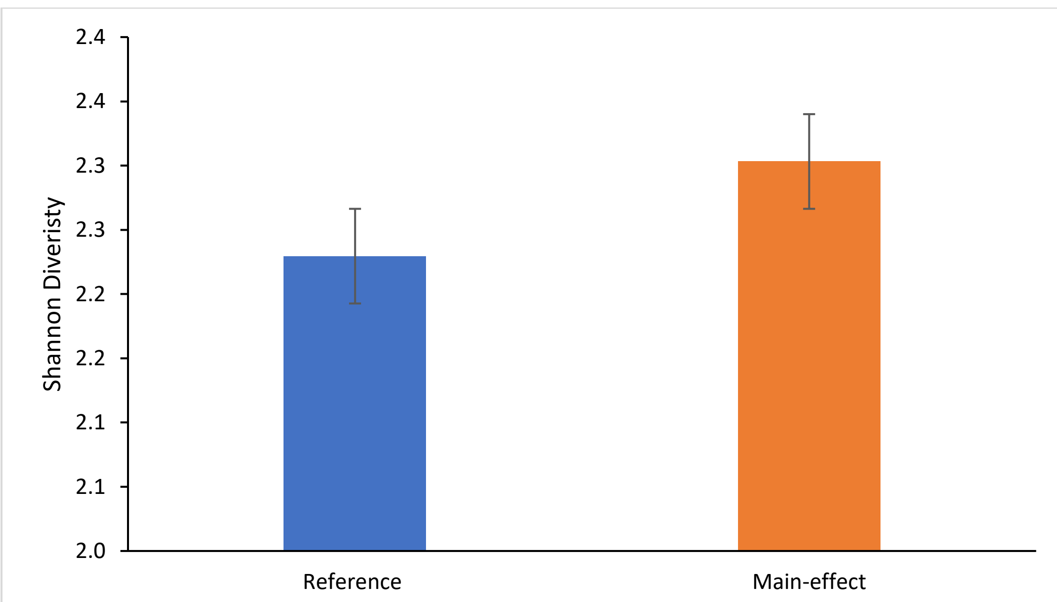

Figure 28. Average Shannon Diversity (+/- standard error) of benthic macroinvertebrates collected from the mid-channel habitat both reference sites and main-effect sites. Reference sites are located 7.8 to 13 rkm above and below the dam, while the main-effect sites are located immediately below the dam to 0.5 km below the dam and 1.2 to 2 rkm above the dam.

Shoreline Macroinvertebrate Sampling Results

We collected 31 macroinvertebrate genera from the shoreline habitat (Table A5). The collection sites paralleled the mid-channel macroinvertebrate sample sites. However, due to low sample sizes or lost samples, we removed three sites (13 km above, 7.8 km above, and 7.8 km below), and limited the data to eight sites (Table 6).

Table 6. Shoreline (multi-habitat) collection sites both above and below the dam. The location is the distance in river kilometers above or below the dam, and the number of times sampled is in parentheses.

Site Designation	Location
Above	1.2 rkm (X3), 2 rkm (X2)
Below	11 rkm, 0.5 rkm, Immediate Below

As only one reference site remained due to lost samples or low sample sizes, we limited the analysis to two factors. We compared the above and below dam sites to each other since the reference site was insufficient for further comparison. We found no significant clustering in the nMDS (stress 0.04) between the above and below dam sites (Figure 29). The site located 11 km below the dam, which we previously used as a reference site appeared distant on the nMDS from the other below dam sites.

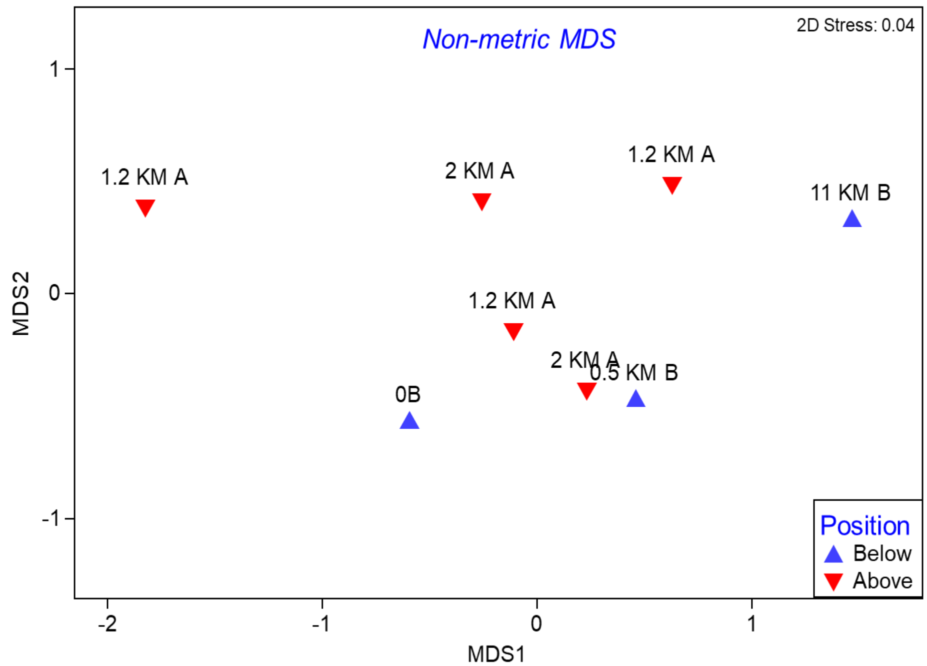

Figure 29. Non-metric multidimensional scaling (target stress < 0.1) of the fourth-root transformed benthic macroinvertebrate samples collected from the shoreline (within one meter of the bank) habitat. Each location represents the distance in river kilometers above or below the dam.

Macroinvertebrate communities within the shoreline habitat were similar above and below the dam (R = -0.005, p = 0.43). EPT percentages were similar within the shoreline habitat above and below the dam (R = -0.067, p = 0.55). We experienced greater species richness and Shannon Diversity indexes below the dam than above the dam (Table 8, Figure 30, Figure 31). We did not detect a significant difference between these indexes within the shoreline habitat. Still, this finding may indicate the shoreline habitat below the dam is preferable over the shoreline habitat above the dam since the dam should not act as a barrier to winged adults.

Table 7. Diversity of benthic macroinvertebrates collected from the shoreline habitat. "Sample" refers to the location in river kilometers above or below the dam. S = species richness, N = number of individuals, H' = Shannon Diversity index. Any entries containing a range indicates more than one sampling occurrence.

Sample	S	N	H'(ln())
2 rkm A	11-18	28-189	1.8-2.31
1.2 rkm A	3-11	43-104	0.3 – 1.73
0 rkm B	13	178	1.84
0.5 rkm B	17	220	1.47
11 rkm B	9	36	1.92

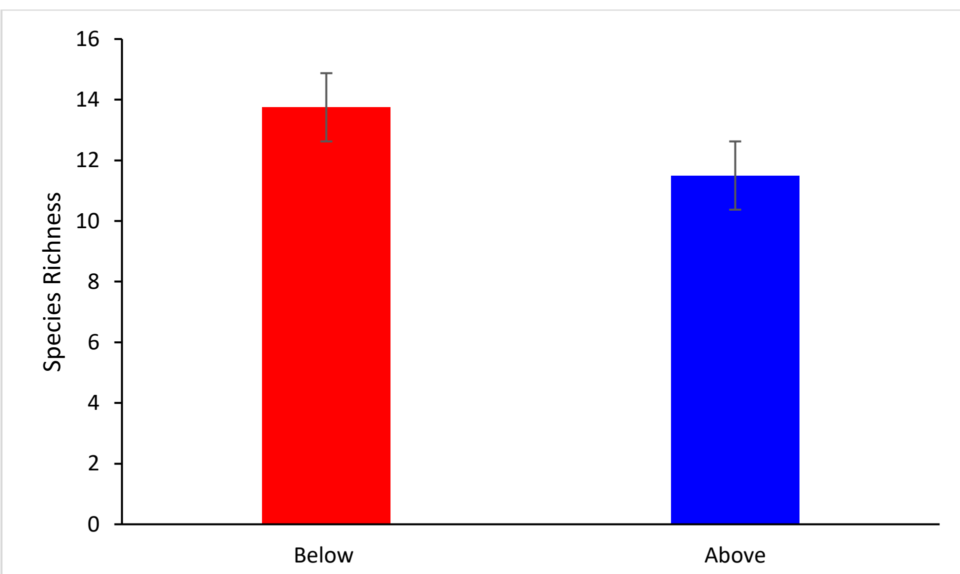

Figure 30. Average species richness (+/- standard error) of shoreline collected macroinvertebrates identified to genera either above or below the dam. The average species richness was calculated from 438 benthic macroinvertebrates collected above the dam and 434 benthic macroinvertebrates collected below the dam.

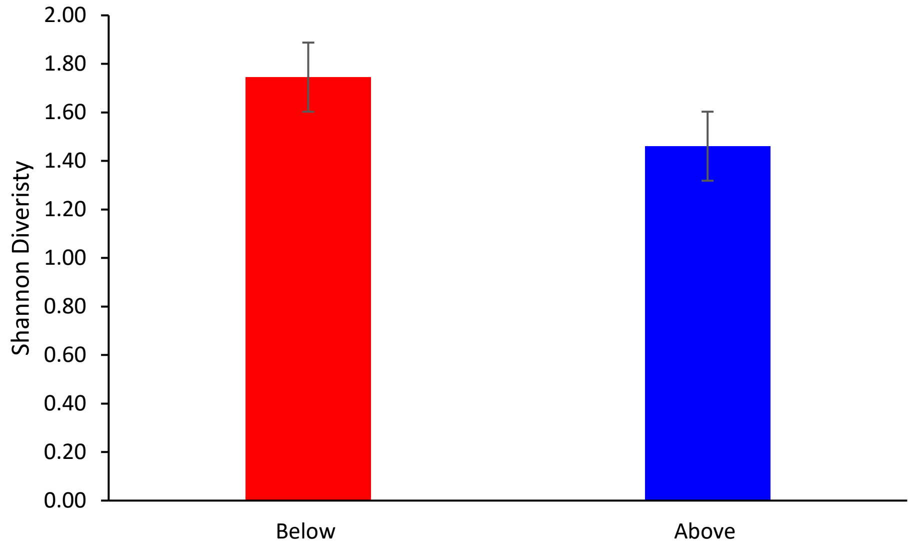

Figure 31. Average Shannon Diversity (+/- standard error) of macroinvertebrates collected shoreline identified to genera either above or below the dam. The average Shannon Diversity was calculated from 438 benthic macroinvertebrates collected above the dam and 434 benthic macroinvertebrates collected below the dam.

Combined Shoreline and Mid-channel

We collected 41 macroinvertebrate genera from eight samplings when the mid-channel and shoreline sampling techniques were combined (Table A7). Due to low sample sizes and missing shoreline samples, some sites were excluded (13 km above, 7.8 km above, 7.8 km below) from the analysis but the sites remained the same as in the shoreline analysis above (Table 6). Similarly, due to the reduced number of reference sites, we confined the analysis to comparing the above and below dam sites.

We observed some clustering of the above dam sites in the two-dimensional nMDS (stress = 0.07, Figure 32). The reference site located farther downstream from the dam appears different on the nMDS than the above dam sites.

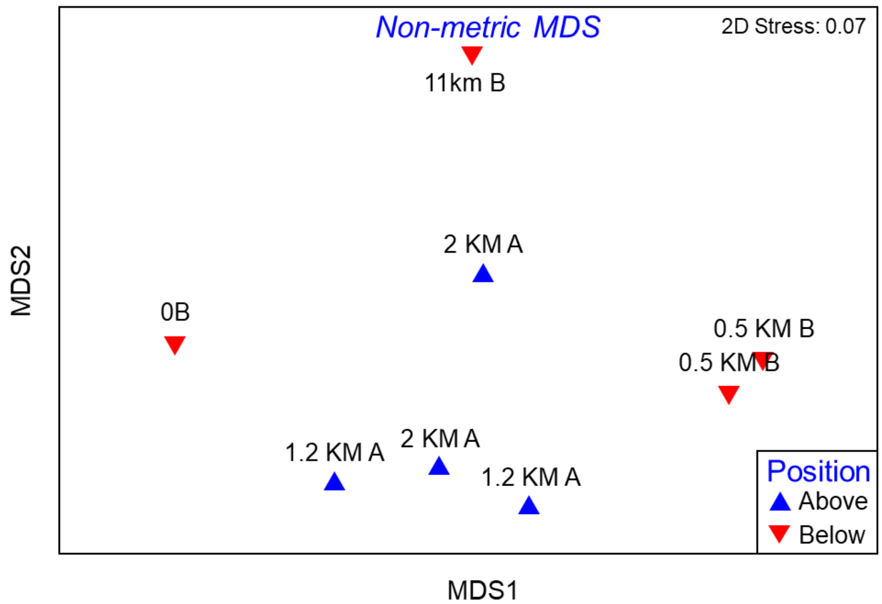

Figure 32. Non-metric multidimensional scaling (target stress < 0.1) of benthic macroinvertebrates collected within each 200 meter site. Each data point is an individual sampling occurrence and represents the distance in river kilometers either above or below the dam.

Macroinvertebrate assemblages collected from both the mid-channel and shoreline habitat were similar both above and below the dam (R = 0.177, p = 0.17 (Table 8)). EPT percentages were similar between above and below dam sites (R = 0.156, p = 0.29). Species richness was slightly greater below the dam versus above the dam (Figure 33). Shannon diversity index was similar for above and below dam sites (Figure 34).

Table 8. Diversity of sampled benthic macroinvertebrates including both shoreline and mid-channel samples. "Sample" refers to one sampling occasion and the distance in river kilometers either above (A) or below (B) the dam. "S" = species richness, "N" = number of individuals collected, "H'" = Shannon Diversity Index. Any entries containing a range indicates more than one sampling occurrence.

Sample	S	N	H'(ln())
2 km A	20-24	226-389	2.49-2.69
1.2 km A	18-20	186-297	2.29-2.33
0 B	20	351	2.28
0.5 km B	21-25	418-419	1.98-2.28
11 km B	21	200	2.56

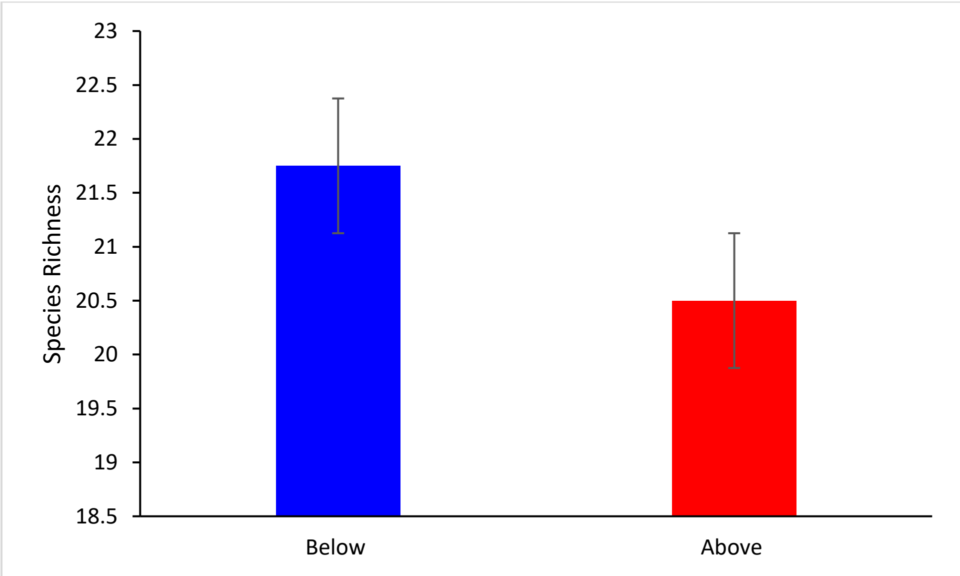

Figure 33. Average species richness (+/- standard error) of benthic macroinvertebrates collected above and below the dam. This data represents macroinvertebrates collected within each 200-meter site and includes both mid-channel samples and shoreline samples. The averages were based upon 1098 benthic macroinvertebrates identified to genera above the dam

and 1388 macroinvertebrates below the dam. Some sample sites were excluded from this analysis due to missing shoreline samples.

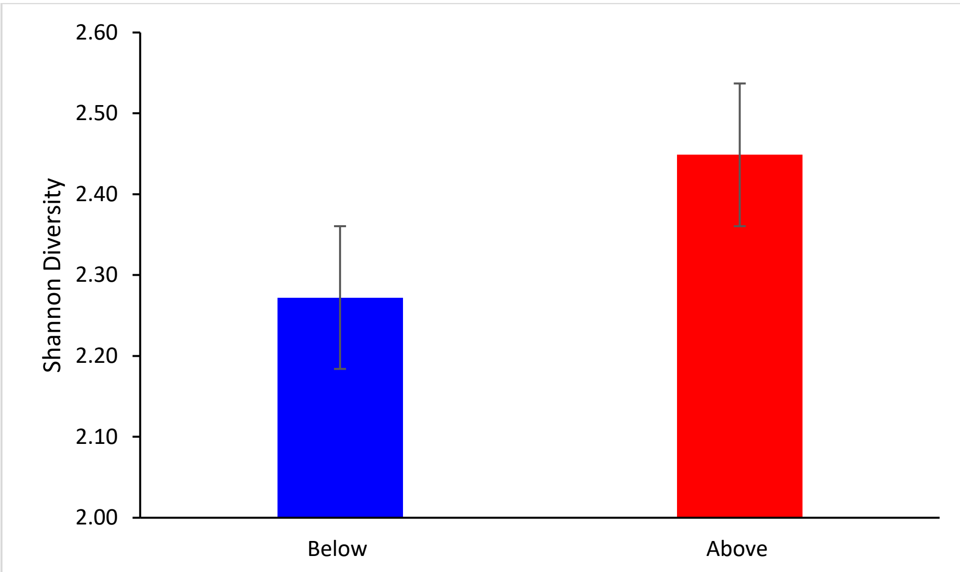

Figure 34. Average Shannon Diversity (+/- standard error) of benthic macroinvertebrates collected above and below the dam. This data represents macroinvertebrates collected within each 200-meter site and includes both mid-channel samples and shoreline samples. The averages were based upon 1098 benthic macroinvertebrates identified to genera above the dam and 1388 macroinvertebrates below the dam. Some sample sites were excluded from this analysis due to missing shoreline samples.

Electrofishing Analysis

We collected a total of 1242 individuals (798 above the dam and 444 below the dam) from 24 species during the 8 sampling occurrences (Table A8). We observed clustering between the above and below dam sites in the two-dimensional nMDS analysis, with a stress value of 0.08. (Figure 35). The four below-dam sites were more tightly correlated than the above-dam sites. The two sites located 1.2 km above the dam were very similar, whereas the sites 1.3 km above the dam seemed different despite having similar sample sizes.

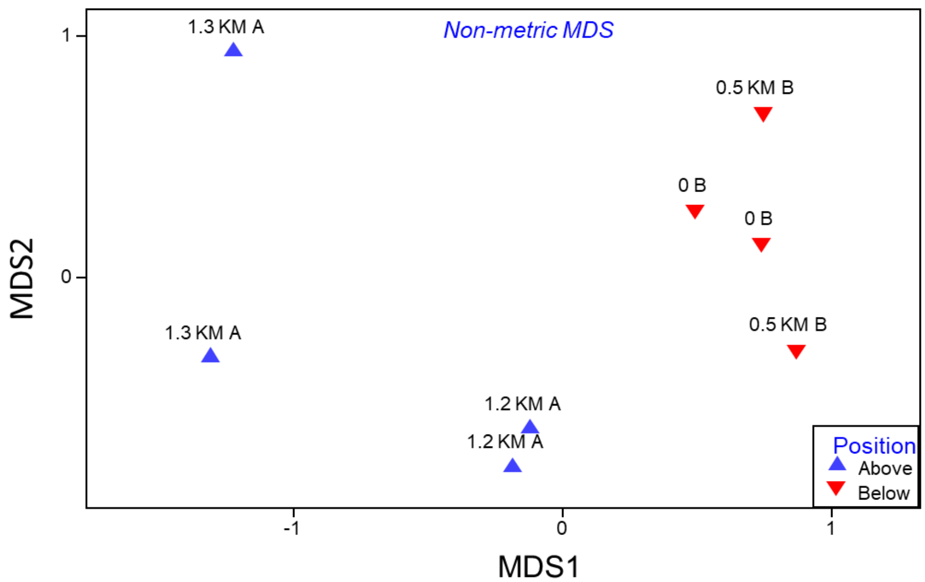

Figure 35. Non-metric multidimensional scaling (target stress <0.1) of fish assemblages collected both above and below the dam from June- August 2021. Each data point represents one sampling occasion. The site names represent the distance in river kilometers either above or below the dam.

Fish assemblages at the above dam sites were different from below dam sites ($R = 0.625$, $p = 0.029$). On average, the species richness and Shannon diversity index were greater below the dam than above the dam (Table 9, Figure 36, Figure 37). Similarly, we found the maximum number of species at the site located 0.5 km below the dam, resulting in 17 species and the highest Shannon Diversity index of 2.2 (Table 9). This finding may result from a higher sample size than other locations. The site located 1.3 km above the dam contained the lowest species diversity.

Table 9. Table of fish species diversity collected from backpack electrofishing of wadable habitat above and below the dam from June – August 2021. The "Sample" represents one sampling occasion and lists the locality of the site in river kilometers both above ("A") and below ("B") the dam. S = number of species, N = number of individuals, H' = Shannon diversity index

Sample	S	N	H'(ln())
0.5 rkm B	17	292	2.20
1.2 rkm A	12	94	2.08
0.5 rkm B	13	95	2.05
0 rkm B	12	158	2.01
1.2 rkm A	15	120	1.93
0 rkm B	13	253	1.85
1.3 rkm A	11	117	1.70
1.3 rkm A	8	113	1.34

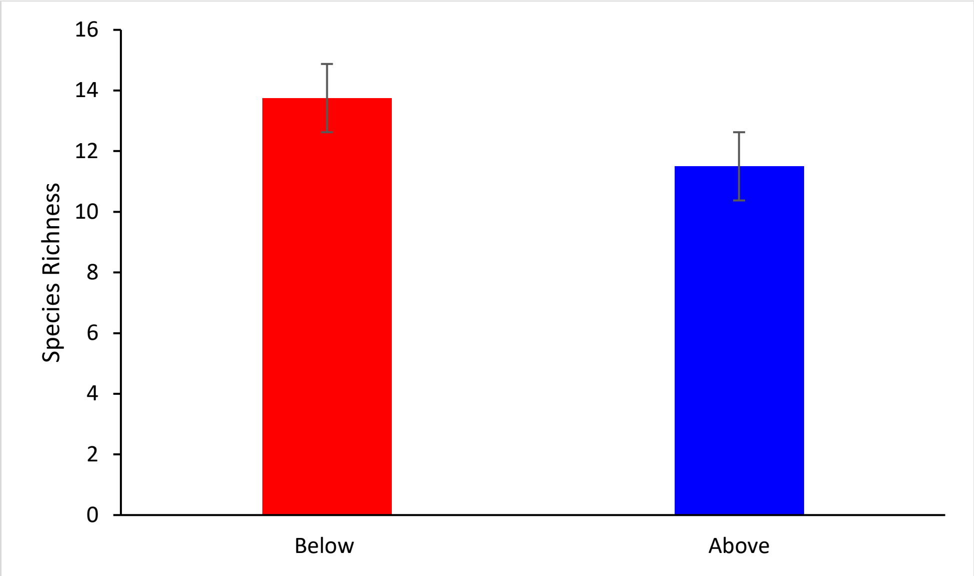

Figure 36. Average species richness (+/- standard error) of fish species collected from backpack electrofishing of wadable habitat.

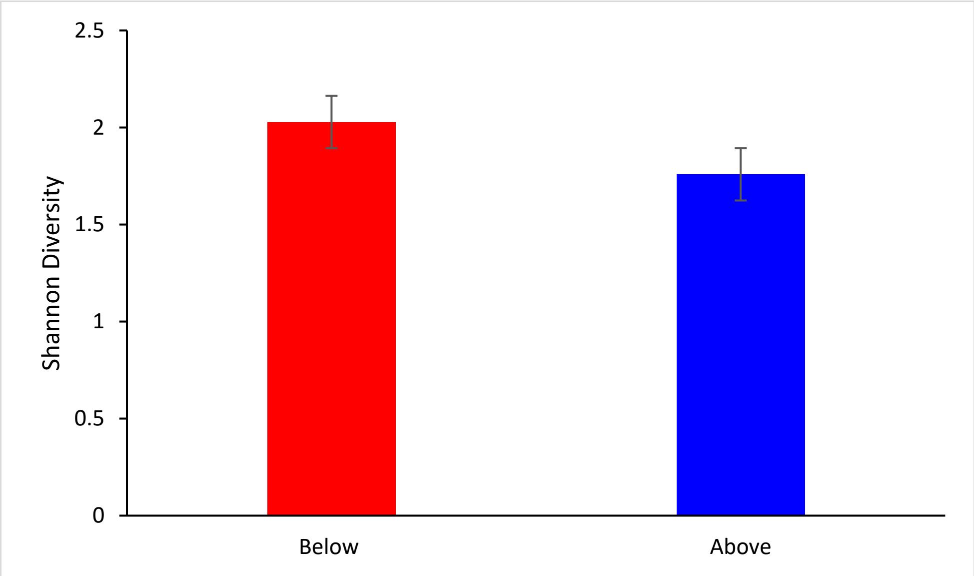

Figure 37. Average Shannon diversity (+/- standard error) of fish species collected from backpack electrofishing of wadable habitat.

We did not detect Wounded Darter (*Etheostoma vulneratum*), Banded Darter (*Etheostoma zonale*), Brown Trout (*Salmo trutta*), Redbreast Sunfish (*Lepomis auratus*), Smoky Dace (*Clinostomus sp*.) and Whitetail Shiner (*Cyprinella galactura*) above the dam but they were present below the dam (Table A8). Mottled Sculpin (*Cottus bairdii* (19.71%)), Greenfin Darter (*Etheostoma chlorobranchium* (18.33%)) and River Chub (Nocomis micropogon (13.24%)) contributed most to the 69% similarity of species found above the dam (Table A9). We did not detect Brook Trout (*Salvelinus fontinalis*), Smallmouth Bass (*Micropterus dolomieu*) and Blacknose Dace (*Rhinichthys obtusus*) below the dam, but they were found above the dam. The Greenfin Darter (*Etheostoma chlorobranchium* (13.91%)), Mottled Sculpin (*Cottus bairdii* (13.53%)) and Tennessee Shiner (*Notropis leuciodus* (11.22%)) contributed most to the 74% similarity of species found below the dam. Wounded Darter (*Etheostoma vuleratum* (11.34%)), Banded Darter (*Etheostoma zonale* (10.44%)), and Gilt Darter (*Percina evides* (8.82%)) contributed most to the 35% dissimilarity among species found both above and below the dam.

DISCUSSION

Although we did not detect any significant differences among habitat characteristics or macroinvertebrate assemblages, we did observe differences in fish assemblages above and below Cullowhee Dam. We detected the presence of six fish species below the dam that we did not find above the dam. Conversely, three fish species were present above the dam but not below the dam. These findings parallel the higher Shannon Diversity and Species Richness indexes below the dam versus above the dam. The habitat was similar above and below the dam. Although not statistically significant, we observed higher percentages of cobble above the dam, with a slight decrease in cobble percentage below the dam. We expected the cobble percentage to be highest immediately below the dam due to the dam filtering sediment and scouring the downstream portion due to the hydraulic jump created by the dam. The depth was not statistically different, but there was an increase in depth below the dam. Macroinvertebrate communities were not statistically different above or below the dam. We found more macroinvertebrate species below the dam, although this result was not statistically significant. Since there are higher species richness below the dam, the habitat below it may be preferable to benthic macroinvertebrates since it is likely not acting as a barrier to them.

After removing one sample site that appeared as an outlier, we found that Cullowhee Dam did not significantly alter riverine habitat conditions. However, we did observe a slight increase in bottom and column velocity at the main-effect sites below the dam, likely due to the hydraulic jump created by the dam. The average depth was greatest at the main-effect sites located below the dam. Csiki & Rhoads (2014) also observed a greater average depth below one of the four low-head dams they studied. The average wetted width within each site was similar except we observed an increase in wetted width for the below dam reference sites. Typically, wetted width is greater above a low-head dam (Fencl et al., 2015; Skalak et al., 2009). Cskiki & Rhoads (2014) observed a greater channel width below three of four low-head dams. They speculated that the dams induced channel widening through bank erosion (Csiki & Rhoads, 2014). Cobble percentage was greatest at all upstream sites compared to downstream sites. There was a decrease in the cobble percentage found at the reference sites located below the dam. Gravel percentages were similar at all the above dam sites. We observed an increase in gravel percentage immediately below the dam, followed by a decrease in gravel percentages at the reference sites below the dam. The observed decrease in gravel and cobble percentages at reference sites below the dam follows Fencl et al. (2015) where they observed a longitudinal recovery of substrate size due to dam effects. This is further supported by the increase of bedrock seen at all reference sites when compared to main-effect sites. Silt percentages were similar at all sites, whereas sand was virtually non-existent at upstream reference sites. This was followed by a subtle increase in sand percentages at the main-effect sites above the dam. The sand percentages were slightly lower at all below-dam sites compared to the above-dam main effect sites. Csiki & Rhoads' (2014) study saw similar effects. They performed a ^{137}Cs isotope analysis of sediment cores above and below two low-head dams. This isotope was a byproduct of nuclear weapon testing and reached maximum deposition in 1963-1964. If a peak of this isotope was found, it could give the researchers an indication of how long these two dams retained sediment. They took stream bed samples with a grab sampler above and below all four dams. Through the ^{137}Cs isotope analysis, they determined that the two dams studied were not retaining sediment for extended periods and concluded that some stored sediment passes over the dam during high flows. The results from the grab sampler, determined that three of the four dams saw a decrease in sand percentages below the dam and found the highest sand percentages above the dam.

However, the differences in sand percentages above and below the dam were not always significantly different. Overall, they determined some fine sediments, such as sand, can bypass dams during high-flow events.

Based on my findings, Cullowhee Dam seems to have minimal effect on the habitat variables measured. As seen in prior literature, the effects of low-head dams on the environment greatly vary depending on individual dam characteristics. Factors that influence the ability of a dam to alter the natural environment are the channel geometry, the river's slope, and the dam's height, in addition to the number of upstream dams and the distance between dams (Fencl et al., 2015). Based upon visual observation, there is likely a significant difference in the habitat immediately above the dam compared to other sites. Due to safety, we only sampled wadable habitat for this study. A significant difference between the main effect and reference sites might have occurred if the habitat had been assessed immediately above the dam. Based upon visual inspection, immediately above the dam, the habitat consists primarily of fine sediment, a deep channel, and more of a lentic environment than other sample sites. This type of environment usually lacks more sensitive macroinvertebrates. If the dam is removed, this finer substrate will transport downstream. Once the substrate is transported downstream, more course substrate preferential to many macroinvertebrate and fish species will likely be revealed. Therefore, if the dam is removed, both fish and macroinvertebrate communities will likely thrive upstream. Removal of the dam should promote diversity and gene flow.

Based on my findings, macroinvertebrate assemblages were similar between main effect and reference sites. EPT percentages did not differ among sites or collection types. When comparing macroinvertebrate communities from a combination of shoreline and mid-channel habitats, we observed an increase in species richness below the dam, accompanied by a decrease in Shannon Diversity below the dam. Therefore, we found more species below the dam, but observed a more even distribution of species above the dam. The macroinvertebrates collected from the mid-channel habitat exhibited higher species richness and a higher Shannon Diversity level above the dam versus below the dam. The macroinvertebrates collected from the shoreline habitat exhibited higher species richness and Shannon Diversity levels below the dam. Based on the previous findings, the Cullowhee Dam is likely not significantly impairing the movement of macroinvertebrates upstream or downstream, especially since many of the collected macroinvertebrates emerge as winged adults and should easily bypass the dam. However, the nMDS of both the shoreline and combined samples indicated a difference between macroinvertebrate communities within the reference and main-effect sites might exist. It is possible that the sites excluded from this analysis due to lost samples or low sample size contributed to this finding, as the sample size was greatly reduced and resulted in the elimination of three out of four reference sites. Further sampling needs to occur to conclude if macroinvertebrate assemblages are similar or different at the test sites. These findings do not align with some past studies, such as Tiemann et al. (2005), Mbaka et al. (2015), and Bredenhand & Samways (2009). Tiemann et al. (2005) found a significant difference in EPT percentages above and below three low-head dams, where EPT percentages were much lower above the low-head dams than below the dams. Mbaka et al. (2015) composed a literature review of 94 articles highlighting the effects of low-head dams on stream habitat conditions and macroinvertebrates. They determined that small impoundments tend to affect macroinvertebrate abundance and species richness. In cases where the macroinvertebrate abundances were similar between reference and main-effect sites, less sensitive macroinvertebrates likely replaced more sensitive species. Bredenhand & Samways (2009) found a significant difference between macroinvertebrates upstream versus downstream of a dam in a biodiversity hotspot. More specifically, there was much higher macroinvertebrate diversity above the dam versus below the dam.

It is important to note that we could not sample macroinvertebrates directly above the dam for safety reasons. Upon visual inspection, the habitat immediately above the dam was comprised mainly of fine sediment and slow-moving water. Therefore, more sensitive macroinvertebrates are likely absent in this region. Most of the collected macroinvertebrates become winged adults later in their life cycle. Therefore, a small, low-head dam such as Cullowhee Dam should not pose as a barrier allowing adults to lay their eggs in any areas with appropriate habitats.

There were significant differences in fish assemblages above and below the Cullowhee Dam. We saw the lowest Shannon Diversity measures at the site located 1.3 km above the dam. In contrast, we found the highest Shannon Diversity measures at the site located 0.5 km below the dam. The average species richness was highest below the Cullowhee Dam. These findings may indicate that the Cullowhee Dam acts as an impassable barrier to the upstream movement of fish since there was insufficient overlap between fish collected above and below the dam. A low-head dam as small as 1.5 meters tall can prevent most fish species from progressing upstream (Porto et al., 1999). Many studies of fish assemblages above and below low-head dams also saw an upstream decrease in species richness (Reyes-Gavilan et al., 1996; Holmquist et al., 1998; March et al., 2003). We did not detect some species above the dam, but they were present below the dam. However, Brook Trout (*Salvelinus fontinalis*) was one of the three species found above the dam, not detected below the dam. Based on historic records from NCDEQ we know that Brook Trout are present below the dam (Couglan & Hall, 2012). Due to gear limitations, only backpack electrofishing of wadable habitat occurred. If we combined boat electrofishing of deeper areas with backpack electrofishing techniques, we would likely have captured more species. Gillette et al. (2005), saw more lentic species immediately above low-head dams with more riffle species downstream of low-head dams. Based upon personal observations, Cullowhee Dam likely follows this pattern since there are predominately sunfish and shiners immediately above the dam and predominately lotic species below the dam.

With limited funding available, researchers should prioritize the removal of dams which will most benefit the environment. Geographic location is an important variable in the effects of dams or their removal. If a watershed has few dams, and a dam lower in the watershed is removed, more connectivity within the watershed is restored (Grill et al., 2014). Conversely, if an isolated dam is removed, the dam’s removal will likely have little effect if there are many more dams in the watershed (Cooper, 2013). It may also be more beneficial to remove dams blocking biota from high-quality upstream habitats (Duda et al., 2008). Removing a dam does not always return the river to pre-dam conditions. Factors such as changes in local and watershed-wide land and water use, water quality, and climate changes can influence the recovery of both the physical conditions and the biota after a dam is removed (Foley et al., 2017). Therefore, researchers must keep their end goal in mind and do proper research before removing a dam to maximize their desired impacts on the environment or biota.

REFERENCES

Allan, J. D. (1995). Modification of running waters by humankind. *Stream Ecology: Structure and Function of Running Waters*, 305–342. https://doi.org/10.1007/978-94-011-0729-7_14

[AFSSD] *American Fisheries Society Southern Division, Trout Committee*. fisheries. (1992, August). Retrieved April 2, 2022, from https://units.fisheries.org/sdafstroutcommittee/wp-content/uploads/sites/25/2017/02/SD-Trout-Comm-stream-sampling-guidelines.pdf

Bredenhand, E., & Samways, M. J. (2009). Impact of a dam on benthic macroinvertebrates in a small river in a biodiversity hotspot: Cape Floristic Region, South Africa. *Journal of Insect Conservation*, *13*(3), 297–307. https://doi.org/10.1007/s10841-008-9173-2

Clarke, K. R., & Gorley, R. N. (2006). *Primer V6: User Manual - Tutorial*. Plymouth Marine Laboratory.

Cooper, A. R. (2013), Effects of dams on streams of the conterminous United States: Characterizing patterns in habitat fragmentation nationally and fluvial fish response in the Midwest, Master's thesis, Mich. State Univ., East Lansing, Mich.

Couglan , D. J., & Hall, J. J. (2012). *Dillsboro Hydroelectric Project's Post-Dam Removal 2011 Biological Monitoring Report*. Edocs.deq.nc.gov. https://edocs.deq.nc.gov/WaterResources/DocView.aspx?id=160185&page=35&

Csiki, S., & Rhoads, B. L. (2010). Hydraulic and geomorphological effects of run-of-river dams. *Progress in Physical Geography: Earth and Environment*, *34*(6), 755–780. https://doi.org/10.1177/0309133310369435

Csiki, S. J., & Rhoads, B. L. (2014). Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology*, *206*, 215–229. https://doi.org/10.1016/j.geomorph.2013.10.009

Cuffney, T.F, M.E. Gurtz, and M.R. Meador. 1993. Methods for Collecting Benthic Invertebrate Samples as Part of the National Water-Quality Assessment Program. U.S. Geological Survey Open-File Report 93-406, Raleigh, North Carolina.

Duda, J. J., Freilich, J. E., & Schreiner, E. G. (2008). Baseline studies in the Elwha River Ecosystem prior to dam removal: Introduction to the special issue. *Northwest Science*, *82*(sp1), 1–12. https://doi.org/10.3955/0029-344x-82.s.i.1

Etnier, D. A., & Starnes, W. C. (2001). *The Fishes of Tennessee*. University of Tennessee Press.

Fencl, J. S., Mather, M. E., Costigan, K. H., & Daniels, M. D. (2015). How big of an effect do small dams have? using geomorphological footprints to quantify spatial impact of low-head dams and identify patterns of across-dam variation. *PLOS ONE*, *10*(11). https://doi.org/10.1371/journal.pone.0141210

Flatley, A., Rutherfurd, I., & Hardie, R. (2018). River channel relocation: Problems and prospects. *Water*, *10*(10), 1360. https://doi.org/10.3390/w10101360

Foley, M. M., Bellmore, J. R., O'Connor, J. E., Duda, J. J., East, A. E., Grant, G. E., Anderson, C. W., Bountry, J. A., Collins, M. J., Connolly, P. J., Craig, L. S., Evans, J. E., Greene, S. L., Magilligan, F. J., Magirl, C. S., Major, J. J., Pess, G. R., Randle, T. J., Shafroth, P. B., Wilcox, A. C. (2017). Dam removal: Listening in. *Water Resources Research*, *53*(7), 5229–5246. https://doi.org/10.1002/2017wr020457

Gaufin, A. R., & Tarzwell, C. M. (1956). Aquatic Macro-Invertebrate Communities as Indicators of Organic Pollution in Lytle Creek. *Sewage and Industrial Wastes*, *28*(7), 906–924. http://www.jstor.org/stable/25033111

Gillette, D. P., Tiemann, J. S., Edds, D. R., & Wildhaber, M. L. (2005). Spatiotemporal patterns of fish assemblage structure in a river impounded by low-head dams. *Copeia*, *2005*(3), 539–549. https://doi.org/10.1643/ce-04-135r2

Gordon, N. D., McMahon, T. A., Finlayson, B. L., Gippel, C. J., & Nathan, R. J. (2006). 5 How to have a field day and still collect some useful information. In *Stream Hydrology: An introduction for ecologists* (Second, pp. 75–125). essay, Wiley.

Grill, G., Ouellet Dallaire, C., Fluet Chouinard, E., Sindorf, N., & Lehner, B. (2014). Development of new indicators to evaluate river fragmentation and flow regulation at large scales: A case study for the Mekong River Basin. *Ecological Indicators*, *45*, 148–159. https://doi.org/10.1016/j.ecolind.2014.03.026

Harvey, R., Lye, L., Khan, A., & Paterson, R. (2011). The influence of air temperature on water temperature and the concentration of dissolved oxygen in Newfoundland Rivers. *Canadian Water Resources Journal*, *36*(2), 171–192. https://doi.org/10.4296/cwrj3602849

Holmquist, J. G., Schmidt-Gengenbach, J. M., & Yoshioka, B. B. (2008). High dams and marine-freshwater linkages: Effects on native and introduced fauna in the Caribbean. *Conservation Biology*, *12*(3), 621–630. https://doi.org/10.1111/j.1523-1739.1998.96427.x

Knight, A. W., & Bottorff, R. L. (1984). The importance of riparian vegetation to stream ecosystems. *California Riparian Systems*, 159–167. https://doi.org/10.1525/9780520322431-025

Larson, D. M., Dodds, W. K., & Veach, A. M. (2018). Removal of woody riparian vegetation substantially altered a stream ecosystem in an otherwise undisturbed grassland watershed. *Ecosystems*, *22*(1), 64–76. https://doi.org/10.1007/s10021-018-0252-2

March, J. G., Benstead, J. P., Pringle , C. M., & Scatena , F. N. (2003). Damming tropical island streams: Problems, solutions, and alternatives. *BioScience*, *53*(11), 1069. https://doi.org/10.1641/0006-3568(2003)053[1069:dtisps]2.0.co;2

Mbaka, J. G., & Wanjiru Mwaniki, M. (2015). A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates. Environmental Reviews, 23(3), 257–262. https://doi.org/10.1139/er-2014-0080

McGill Associates, P.A., Schnabel Engineering P.C., & Equinox Environmental. (2017, July). Cullowhee Dam Evaluation Western Carolina University Tuckaseigee Water & Sewer Authority Jackson County, North Carolina.

Merritt, R. W., & Cummins, K. W. (2008). Use of Aquatic Insects In Biomonitoring. In *An introduction to the aquatic insects of North America* (pp. 123–137). essay, Kendall/Hunt Pub. Co.

[USACE] National Inventory of Dams (NID) Data Team. Corps Map: National inventory of dams. U.S.Army Core of Engineers. Available at https://nid.sec.usace.army.mil/#/, accessed 4 May 2022.

[NCDEQ] North Carolina Department of Environmental Quality (2012). Little Tennessee River Basin Plan: Tuckasegee River Subbasin (HUC 0610203). https://www.deq.nc.gov/water-quality/planning/bpu/hiwassee/hiwassee-plans/2012-plan/3-06010203-tuckasegee/download

Page, L. M., & Burr, B. M. (2011). *Peterson Field Guide to freshwater fishes of North America, north of Mexico*. Houghton Mifflin.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The Natural Flow Regime. BioScience, 47(11), 769–784. https://doi.org/10.2307/1313099

Porto, L. M., McLaughlin, R. L., & Noakes, D. L. (1999). Low-head barrier dams restrict the movements of fishes in two Lake Ontario streams. *North American Journal of Fisheries Management*, *19*(4), 1028–1036. https://doi.org/10.1577/1548-8675(1999)019<1028:lhbdrt>2.0.co;2

Reiser, D.W. and R.T. Peacock. 1985. A technique for assessing upstream fish passage problems at small scale hydropower developments. Proceddings of the Symposium on Small Hydropower and Fisheries May 1-3, Aurora, Colorado.

Reyes-Gavilan, F. G., Garrido, R., Nicieza, A. G., Toledo, M. M., & Brana, F. (1996). Fish community variation along physical gradients in short streams of northern Spain and the disruptive effect of Dams. *Hydrobiologia*, *321*(2), 155–163. https://doi.org/10.1007/bf00023171

Rosenberg, D.M. and Resh, V.H. (1993) Introduction to Freshwater Biomonitoring and Benthic Macroinvertebrates. In: Rosenberg, D.M. and Resh, V.H., Eds., Freshwater Biomonitoring and Benthic Macroinvertebrates, Chapman/Hall, New York, 1-9.

Saleh, A., 1993. Soil roughness measurement: chain method. Journal of Soil and Water Conservation, 48(6), pp.527-529.

Schmutz, S., & Moog, O. (2018). Dams: ecological impacts and management. In *Riverine ecosystem management* (pp. 111-127). Springer, Cham

Sendzimir, J., & Schmutz, S. (2018). Challenges in Riverine Ecosystem Management. *Riverine Ecosystem Management*, 1–16. https://doi.org/10.1007/978-3-319-73250-3_1

Skalak, K., Pizzuto, J., & Hart, D. D. (2009). Influence of small dams on downstream channel characteristics in Pennsylvania and Maryland: Implications for the long-term geomorphic effects of dam removal. *JAWRA Journal of the American Water Resources Association*, *45*(1), 97–109. https://doi.org/10.1111/j.1752-1688.2008.00263.x

Simons, D. B. (1979). Effects of stream regulation on channel morphology. *The Ecology of Regulated Streams*, 95–111. https://doi.org/10.1007/978-1-4684-8613-1_7

Temple, G. M., & Pearsons, T. N. (2007). Electrofishing: backpack and drift boat. Salmonid field protocols handbook: techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryland, 95-132.

Tiemann, J. S., Gillette, D. P., Wildhaber, M. L., & Edds, D. R. (2005). Effects of lowhead dams on the ephemeropterans, plecopterans, and Trichopterans Group in a North American River. *Journal of Freshwater Ecology*, *20*(3), 519–525. https://doi.org/10.1080/02705060.2005.9664767

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*(1), 130–137. https://doi.org/10.1139/f80-017

Watson, S. B., Miller, C., Arhonditsis, G., Boyer, G. L., Carmichael, W., Charlton, M. N., Confesor, R., Depew, D. C., Höök, T. O., Ludsin, S. A., Matisoff, G., McElmurry, S. P., Murray, M. W., Peter Richards, R., Rao, Y. R., Steffen, M. M., & Wilhelm, S. W. (2016). The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful Algae*, *56*, 44–66. https://doi.org/10.1016/j.hal.2016.04.010

Zeiringer, B., Seliger, C., Greimel, F., & Schmutz, S. (2018). River hydrology, flow alteration, and environmental flow. *Riverine Ecosystem Management*, 67–89. https://doi.org/10.1007/978-3-319-73250-3_4

APPENDIX

Table A1. Summary data of the combined shoreline and mid-channel habitat variables collected from each sample site. The distance with each sample site represents the distance in rkm above or below the dam. A = Above, B = Below. Refer to list of abbreviations for variables.

Habitat Variable	11 km B	7.8 km B	0.5 km B	0 km B	1.2 km A	2 km A	7.8 km A	13 km A
Avg. Depth (m)	0.50	0.45	0.58	0.66	0.54	0.42	0.44	0.34
Avg. BV (m/s)	0.14	0.12	0.25	0.14	0.13	0.21	0.10	0.31
Avg. CV (m/s)	0.33	0.21	0.43	0.32	0.27	0.44	0.19	0.58
Bed per	37.20	38.70	8.50	0.00	0.60	1.30	25.73	0.00
Bdr per	10.10	15.40	11.60	18.50	10.30	17.30	12.30	1.30
Cob per	15.20	12.50	28.20	31.80	36.10	35.80	33.30	27.10
Grv per	16.20	8.60	19.40	24.00	15.20	17.30	13.40	43.10
Snd per	13.50	21.50	18.70	21.90	25.50	18.60	7.20	20.30
Slt per	5.70	1.80	10.50	2.40	6.50	2.00	8.00	2.00
Wd per	2.00	1.40	3.10	1.40	5.80	7.80	0.00	6.20
Avg WW	62.50	70.20	36.80	35.10	32.90	37.80	34.95	8.50
Gradient	0.00042	0.00018	0.00018	0.00010	-0.00004	0.00026	0.00014	-0.00004
Chain Ro	4.29	4.40	4.38	4.44	4.27	4.36	4.32	4.51

Table A2. Summary habitat data of the mid-channel habitat within each site. The distance with each sample site represents the distance in rkm above or below the dam. A = Above, B = Below. Refer to list of abbreviations for variables.

Habitat Variable	11 km B	7.8 km B	0.5 km B	0 km B	1.2 km A	2 km A	7.8 km A	13 km A
Avg. Depth (m)	0.56	0.6	0.71	0.86	0.67	0.49	0.3	0.6
Avg. BV (m/s)	0.14	0.06	0.42	0.17	0.18	0.33	0.06	0.29
Avg. CV (m/s)	0.36	0.36	0.6	0.45	0.38	0.56	0.09	0.54
Bed per	55.7	50.3	11.6	0	1.1	1.1	32.7	0
Bdr per	5.7	18.2	7.2	15.7	9.7	21.5	14.5	9
Cob per	9.7	11.9	40.9	32	51.6	48.4	36.5	40.7
Grv per	20.5	0.6	28.7	33.7	16.7	22	5	16.4
Snd per	8	18.9	9.9	18.6	19.9	6.5	9.4	33.9
Slt per	0.6	0	1.7	0	0	0	1.9	0
Wd per	0	0	0	0	1.1	0.5	0	0

Table A3. Summary habitat data of the shoreline habitat within each site. The distance with each sample site represents the distance in rkm above or below the dam. Refer to list of abbreviations for variables.

Habitat Variable	11 km B	7.8 km B	0.5 km B	0 km B	1.2 km A	2 km A	7.8 km A	13 km A
Avg. Depth (m)	0.42	0.39	0.37	0.37	0.34	0.31	0.30	0.40
Avg. BV (m/s)	0.14	0.14	0.12	0.07	0.06	0.15	0.06	0.15
Avg. CV (m/s)	0.29	0.26	0.18	0.13	0.12	0.26	0.09	0.28
Bed per	10.60	20.70	3.50	0.00	0.00	1.70	16.20	0.00
Bdr per	17.70	12.10	18.60	22.50	11.10	10.70	9.40	1.60
Cob per	19.50	13.80	8.00	31.70	12.70	16.50	29.10	25.60
Grv per	9.70	19.80	4.40	10.00	12.70	9.90	24.80	17.60
Snd per	23.00	25.90	32.70	26.70	34.90	37.20	4.30	33.60
Slt per	14.20	4.30	24.80	5.80	15.90	5.00	16.20	4.80
Wd per	5.30	3.40	8.00	3.30	12.70	19.00	0.00	16.80

Table A4. Raw data of benthic macroinvertebrates identified to genera collected from the mid-channel habitat. The distance with each sample site represents the distance in rkm above or below the dam.

Macroinvertebrate Taxa	11 km B	7.8 km B	0.5 km B	0.5 km B	0 km B	0 km B	0 km B	1.2 km A	1.2 km A	1.2 km A	2 km A	2 km A	2 km A	7.8 km A	13 km A
Drunella	1	3	15	1	1	2	1	1	6	3	4	4	14	5	1
Attenella	4	0	9	0	7	0	25	0	3	14	21	4	0	0	0
Seratella	1	6	0	8	27	0	0	0	3	3	4	5	0	3	1
Ephemerella	3	10	0	1	0	0	13	0	0	0	18	3	0	8	0
Heptagenia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maccaffertium	3	2	2	1	1	4	5	0	6	15	10	7	3	4	0
Leucrocucta	0	0	0	0	2	0	1	10	0	3	0	0	0	0	0
Rhithrogena	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Baetis	7	6	3	10	30	6	3	36	16	7	11	27	17	20	1
Heterocoleon	0	0	0	0	0	0	6	0	3	0	3	0	0	0	0
Ameletus	8	0	0	3	0	5	5	15	0	16	3	0	4	2	0

Table A4 (cont'd). Raw data of benthic macroinvertebrates identified to genera collected from the mid-channel habitat. The distance with each sample site represents the distance in rkm above or below the dam.

	11 km B	7.8 km B	0.5 km B	0.5 km B	0 km B	0 km B	0 km B	1.2 km A	1.2 km A	1.2 km A	2 km A	2 km A	2 km A	7.8 km A	13 km A
Isonychia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pteronarcys	0	0	1	3	1	0	0	0	0	0	0	0	2	0	0
Acroneuria	4	0	0	9	4	6	3	7	0	10	0	3	1	2	1
Agnetina	0	0	0	55	0	6	21	1	21	28	10	22	3	28	38
Paragnetina	0	0	1	0	32	2	0	17	0	0	0	0	0	0	1
Neoperla	25	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Perlesta	4	0	0	0	1	0	4	0	0	0	3	0	0	0	0
Alloperla	1	0	1	9	0	7	0	14	2	2	4	0	1	5	5
Brachycentrus	5	23	27	3	0	2	6	0	7	0	0	9	16	21	29
Micrasema	11	72	22	1	2	4	10	2	0	0	11	22	17	18	10
Hydropsyche	20	17	15	41	16	47	19	49	41	37	39	18	38	17	0
Rhyacophila	1	0	1	2	0	0	1	1	1	1	6	1	2	5	3

Table A4 (cont'd). Raw data of benthic macroinvertebrates identified to genera collected from the mid-channel habitat. The distance with each sample site represents the distance in rkm above or below the dam.

	11 km B	7.8 km B	0.5 km B	0.5 km B	0 km B	0 km B	0 km B	1.2 km A	1.2 km A	1.2 km A	2 km A	2 km A	2 km A	7.8 km A	13 km A
Phylocentropus	0	0	0	2	0	0	0	2	0	17	2	0	0	0	0
Oecetis	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Psilotreta	9	0	0	0	0	0	0	0	0	0	0	0	0	7	0
Lepidostoma	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Optioservus	41	41	75	22	8	32	11	14	27	2	9	45	32	25	28
Psephenus	2	0	4	0	0	0	0	1	2	0	1	3	0	3	0
Chironomus	8	3	15	28	11	48	39	14	28	35	14	13	15	18	17
Prosimulium	0	0	0	4	0	1	0	7	0	0	0	2	0	0	0
Atherix	0	0	0	1	0	9	0	4	0	0	0	0	0	0	1
Antocha	0	0	0	0	0	0	0	0	1	0	2	3	12	1	0
Tipula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemerodromia	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0

Table A5. Raw data of benthic macroinvertebrates identified to genera collected from the shoreline habitat. The distance with each sample site represents the distance in rkm above or below the dam.

	11 km B	0.5 km B	0 km B	1.2 km A	1.2 km A	1.2 km A	2 km A	2 km A
Baetis	1	8	52	76	2	36	38	14
Heterocoleon	0	4	9	2	0	0	0	0
Ameletus	5	0	0	0	0	2	0	0
Baetisca	0	0	0	0	0	1	0	1
Attenella	0	1	10	2	0	0	25	3
Ephemerella	3	1	6	2	0	0	14	1
Eurylophella	0	0	1	0	0	0	0	0
Drunella	4	1	0	1	0	4	2	1
Seretella	0	1	0	0	0	2	9	0
Maccaffertium	0	1	0	0	0	0	16	0
Heptagenia	0	0	1	0	0	0	0	0
Leucrocuta	0	0	0	0	0	0	5	0
Tricorythodes	0	0	0	0	0	0	0	1
Angetina	0	0	7	3	1	0	4	2
Acroneuria	0	0	1	0	0	0	0	0
Paragnetina	0	0	0	0	0	0	0	0
Alloperla	0	1	0	0	0	0	0	0
Perlesta	1	0	0	0	0	0	0	0
Brachycentrus	11	11	0	0	0	6	1	1
Micrasema	0	5	1	4	0	2	3	0
Apatania	0	5	0	1	0	8	7	0
Hydropsyche	4	8	19	1	0	0	2	0
Phylocentropus	0	1	0	0	0	0	1	0
Psilotreta	1	0	0	0	0	0	0	0
Dubiraphia	0	0	0	0	0	0	0	0
Optioservus	6	30	1	6	0	10	17	1

Table A6(cont'd). Raw data of benthic macroinvertebrates identified to genera collected from the shoreline habitat. The distance with each sample site represents the distance in rkm above or below the dam.

	11 km B	0.5 km B	0 km B	1.2 km A	1.2 km A	1.2 km A	2 km A	2 km A
Chironomus	0	137	59	5	40	2	41	1
Antocha	0	4	0	1	0	0	1	0
Hemerodromia	0	1	0	0	0	0	0	0
Prosimulium	0	0	11	0	0	0	2	2

Table A7. Raw data of benthic macroinvertebrates identified to genera collected from the shoreline and mid-channel habitat. The distance with each sample site represents the distance in rkm above or below the dam.

	11 km B	0.5 km B	0.5 km B	0 km B	1.2 km A	1.2 km A	2 km A	2 km A
Drunella	5	16	16	1	6	4	5	6
Attenella	4	10	10	35	3	16	7	46
Seratella	1	1	1	0	3	3	5	13
Ephemerella	6	1	1	19	0	2	4	32
Eurylophella	0	0	0	1	0	0	0	0
Heptagenia	0	2	0	1	0	0	0	0
Maccaffertium	3	1	3	5	6	15	7	26
Leucrocucta	0	0	0	1	0	3	0	5
Rhithrogena	0	3	0	0	0	0	0	0
Baetis	8	8	11	64	16	83	41	49
Baetisca	0	0	0	0	0	0	1	0
Heterocoleon	0	4	4	6	3	2	0	3
Ameletus	13	0	0	5	2	16	0	3
Isonychia	0	0	0	0	0	0	0	0
Tricorythodes	0	1	0	0	0	0	1	0
Pteronarcys	0	0	1	0	0	0	0	0
Acroneuria	4	0	0	4	0	10	3	0
Agnetina	0	1	0	28	23	31	24	14
Paragnetina	0	0	1	0	0	0	0	0
Neoperla	25	0	0	0	0	0	0	0
Perlesta	5	1	0	4	0	0	0	3
Alloperla	1	39	2	0	2	2	0	4
Brachycentrus	16	22	38	6	7	0	10	1
Micrasema	11	20	27	11	0	4	22	14
Hydropsyche	24	9	23	38	41	38	18	41
Rhyacophila	1	7	1	1	1	1	1	6

Table A6 (cont'd). Raw data of benthic macroinvertebrates identified to genera collected from the shoreline and mid-channel habitat. The distance with each sample site represents the distance in rkm above or below the dam.

	11 km B	0.5 km B	0.5 km B	0 km B	1.2 km A	1.2 km A	2 km A	2 km A
Apatainia	5	5	13	0	6	1	7	25
Phylocentropus	0	1	1	0	0	17	0	3
Oecetis	0	0	0	0	0	0	0	0
Psilotreta	10	0	0	0	0	0	0	0
Cryptochia	0	0	0	0	0	0	0	7
Lepidostoma	1	0	0	0	0	0	0	0
Dubiraphia	0	75	0	0	1	0	0	0
Optioservus	47	34	105	12	28	8	46	26
Psephenus	2	15	4	0	2	0	3	2
Chironomus	8	137	152	98	35	40	14	55
Atherix	0	0	0	0	0	0	0	0
Prosimulium	0	0	0	11	0	0	4	2
Antocha	0	4	4	0	1	1	3	3
Tipula	0	0	0	0	0	0	0	0
Hemerodromia	0	1	1	0	0	0	0	0

Table A8. Raw data of backpack electrofishing results from June-August 2021. The associated distance is the distance above or below the dam in rkm.

	0.5 km B	0.5 km B	0 km B	0 km B	1.2 km A	1.2 km A	2 km A	2 km A
Banded Darter (*Ethesotoma zonale*)	7	6	2	5	0	0	0	0
Blacknose Dace (*Rhinichthys obtusus*)	0	0	0	0	1	0	0	0
Brook Trout (*Salvelinus fontinalis*)	0	0	0	0	1	2	0	0
Brown Trout (*Salmo trutta*)	0	1	0	0	0	0	0	0
Central Stoneroller (*Campostoma anomalum*)	1	15	2	4	2	1	0	0
Fatlips Minnow (*Phenacobius crassilabrum*)	0	0	0	1	1	2	0	0
Gilt Darter (*Percina evides*)	13	9	22	15	4	7	0	0
Greenfin Darter (*Etheostoma chlorobranchium*)	28	58	30	73	36	17	37	28
Mountain Brook Lamprey (*Icthyomyzon greelyi*)	0	6	2	1	1	0	4	1
Longnose Dace (*Rhinichthys cataractae*)	2	0	0	0	0	0	0	1
Mottled Sculpin (*Cottus bairdii*)	16	79	41	87	35	25	54	42
Mirror Shiner (*Notropis spectrunculus*)	1	21	27	0	2	2	0	0
Northern Hogsucker (*Hypentelium nigricans*)	0	17	1	0	2	0	0	4
Redbreast Sunfish (*Lepomis auritus*)	0	2	0	0	0	0	0	0
River Chub (*Nocomis micropogon*)	2	43	3	6	18	11	3	25
Rock Bass (*Ambloplites rupestris*)	0	4	0	1	5	6	0	2
Smallmouth Bass (*Micropterus dolomieu*)	0	0	0	0	0	0	0	1

Table A7 (cont'd). Raw data of backpack electrofishing results from June-August 2021. The associated distance is the distance above or below the dam in rkm.

	0.5 km B	0.5 km B	0 km B	0 km B	1.2 km A	1.2 km A	2 km A	2 km A
Smoky Dace *(Clinostomus sp.)*	0	1	0	0	0	0	0	0
Tennessee Shiner (*Notropis leuciodus*)	14	19	12	22	8	14	3	9
Tuckasegee Darter (*Etheostoma gutselli*)	2	1	0	13	3	1	2	1
Warpaint Shiner (*Luxilus coccogenis*)	6	5	7	10	1	6	9	3
Whitetail Shiner (*Cyprinella galactura*)	1	0	0	0	0	0	0	0
Wounded Darter (*Etheostoma vulneratum*)	2	5	9	15	0	0	0	0

Table A9. Similarity percentages breakdown of fish species collected above and below the dam through backpack electrofishing. Av.Abund Above = the average amount of a given species collected above the dam. Av. Abund Below = the average amount of a given species collected below the dam. Contrib% = the percentage of contribution to the dissimilarity of species found above and below the dam. Cum.% = the cumulative percentage of species contributions to the dissimilarity of species found above and below the dam.

Species	Av.Abund Above	Av.Abund Below	Contrib%	Cum.%
Wounded Darter (*Etheostoma vulneratum*)	0	1.6	11.34	11.3
Banded Darter (*Ethesotoma zonale*)	0	1.47	10.44	21.8
Gilt Darter (*Percina evides*)	0.76	1.94	8.82	30.6
Mirror Shiner (*Notropis spectrunculus*)	0.59	1.36	7.85	38.4
Central Stoneroller (*Campostoma anomalum*)	0.55	1.39	6.2	44.6
Northern Hogsucker (*Hypentelium nigricans*)	0.65	0.76	5.71	50.4
Rock Bass (*Ambloplites rupestris*)	1.06	0.6	5.68	56.0
Mountain Brook Lamprey (*Icthyomyzon greelyi*)	0.85	0.94	4.23	60.3
River Chub (*Nocomis micropogon*)	1.86	1.66	4.07	64.3
Tuckasegee Darter (*Etheostoma gutselli*)	1.13	1.02	3.92	68.3
Fatlips Minnow (*Phenacobius crassilabrum*)	0.55	0.25	3.78	72.0
Brook Trout (*Salvelinus fontinalis*)	0.55	0	3.67	75.7
Longnose Dace (*Rhinichthys cataractae*)	0.25	0.3	3.14	78.9
Mottled Sculpin (*Cottus bairdii*)	2.48	2.64	2.98	81.8
Smoky Dace (*Clinostomus sp.*)	0.25	0.25	2.67	84.5
Tennessee Shiner (*Notropis leuciodus*)	1.67	2.01	2.57	87.0
Greenfin Darter (*Etheostoma chlorobranchium*)	2.31	2.58	2.3	89.4
Whitetail Shiner (*Cyprinella galactura*)	0	0.25	1.96	91.3