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Effects of beaver dam analogs on stream ecosystem function of Crab Creek, Washington State

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EFFECTS OF BEAVER DAM ANALOGS ON STREAM ECOSYSTEM FUNCTION OF CRAB CREEK, WASHINGTON STATE

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Abstract

This study documents the effects of beaver dam analogs (BDAs) on nutrient transport, fish community composition, macroinvertebrate drift, and benthic macroinvertebrate communities of Crab Creek, WA, USA. In 2019, the U.S. Fish and Wildlife Service (USFWS), and Natural Resource Conservation Service (NRCS) placed 25 BDAs in Crab Creek on a section of private land near Harrington, WA. Beaver dam analogs are structures placed in streams to mimic the ecosystem effects of beaver activity and are increasingly used as a stream restoration technique. The primary goals of placing these BDAs in the stream was to impound sediment and create a new floodplain at the currently incised stream channel. While BDAs are increasingly used as a stream restoration technique, there is limited research on their impacts on stream ecosystem function. Investigating how BDAs effect nutrient retention, macroinvertebrate communities, and fish community composition will help inform practitioners about the effectiveness of this restoration strategy.

Crab Creek had a significantly higher density of red sided shiners (*Richardsonius balteatus*) ($p=0.00175$) in the BDA reach compared to control reaches. When comparing the BDA reach to the control sites, there were no significant differences in nutrient retention in the BDA site. Macroinvertebrate community response had limited statistically significant differences when compared to the control sites. However, there were significant changes from 2009 to 2020 when comparing benthic macroinvertebrate assemblages, probably in response to factors other than BDA installation. Altogether, few effects of BDA installation were detected for nutrient retention, macroinvertebrate communities, and fish community composition. BDAs are a process-based restoration technique that requires a significant change in physical ecosystem parameters before any changes are likely to be seen in the biological community or ecosystem

processes. Changes to geomorphology of the stream could potentially take time, as these restoration techniques require stream energy to alter the physical parameters of the stream. Since BDA installation in Crab Creek, no significant high flow events have occurred. Without early spring flood events, changes in the nutrient dynamics, and macroinvertebrates communities could be subtle, or undetectable. This research will ultimately contribute to the current limited understanding of the effects of BDAs on stream ecosystem function.

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Introduction

North American beavers (*Castor candensis)* were nearly extirpated from the United States as they were a significant part of the fur trade. Estimates of North American beaver populations before European settlers arrived are 60 - 400 million (Baker and Hill 2003). Management plans and recovery efforts have stabilized the beaver population in the United States to around 6-12 million (Naiman et al. 1988). While beaver populations have rebounded, much of their former habitat lacks the woody debris necessary for beavers to colonize (Pilloid et al. 2018).

Beavers' role as ecosystem engineers has been widely accepted. Beavers and their dams disrupt flow regimes by creating lentic habitat, establishing floodplains, restructuring nutrient dynamics through increased deposition and interactions with nutrient-cycling organisms, and retain sediment in ponds to prevent downstream stream incision in streams (Naiman et al. 1986). Beaver dams are documented to create habitat heterogeneity and increase invertebrate and fish biodiversity (Smith and Mather 2013).

Beavers and the structures they create have impacted fish populations by increasing the amount of rearing habitat, habitat heterogeneity, and increasing fish biodiversity in streams that they inhabit (Bowes et al. 2016, Smith and Mather 2013). Channel-spanning structures placed in streams, such as beaver dams, could potentially have deleterious effects on local fish populations if they impede fish movement. Lokteff et al. (2013) found that both cutthroat trout (*Oncorhynchus clarkii*) and brook trout (*Salvelinus fontinalis*) were able to move through the beaver dams, but brown trout (*Salmo trutta*) showed a significant reduction in movement through the dams, indicating the ability to migrate through or around beaver dams may be species-specific. In general, speculation that beaver dams restrict movement of fish has been anecdotal with little data to support that these structures inhibit migration (Kemp et al. 2012) and more evidence is needed. There is potential that the short-term studies conducted so far may not document longer-term responses of fish assemblages to beaver impoundments (Quinn and Kwak 2013).

Natural beaver dams have the ability to retain nutrients with their impounding of water and sediment (Puttock et al. 2018). Wegner et al. (2017) noted significant retention of total dissolved N in beaver mediated ponds in a wide valley in Colorado. Significantly increased amount of nitrogen, phosphorous, nitrate, and nitrite were documented in beaver pond sediment, and significant amounts of nitrites and nitrates were found in water samples when compared to sites with no history of beaver activity (Lizarralde et al. 1996). In contrast, Wang et al. (2007) found that both nitrate and soluble reactive phosphate (SRP) concentrations increased downstream of beaver impoundments, but only during low flows, suggesting increased nutrient input from groundwater at low flows as a result of beaver impoundment.

Beaver dams' impact on macroinvertebrates is driven by the creation of lentic habitat and increased sediment deposition. Total invertebrate density and biomass can be higher in beaver impoundments than non-impounded areas (McDowell and Naiman 1986). However, diversity can locally decrease (Simanonok et al. 2011, Law et al. 2016), and the composition of the community shifts to organisms such as Chironomidae and oligochaetes that perform well in habitats with high levels of fine sediment (Margolis et al. 2001). Invertebrates that are less tolerant of sediment or that depend on flowing water may decrease in abundance. Margolis et al. 2001, observed significant decreases in the abundance of filter-feeding invertebrates in beaver impoundments. Simanonok et al. (2011) observed a significant decrease in all functional-feeding groups except collector-gatherers. Nonetheless, beaver impoundments can increase beta and gamma diversity, particularly in streams where lentic habitats are lacking (Law et al. 2016).

This study does not aim to determine the effects of natural beaver dams, instead this study will determine any effects of BDAs on their effects on stream ecosystem function. To mimic the ecosystem effects of beaver activity, restoration managers are increasingly installing BDAs. Posts are driven into the substrate and woven with saplings to create a semi-permeable impoundment. The designs of these structures are variable depending on goals and decisions of restoration managers. Common goals of BDA restoration are to reconnect or reestablish floodplains, increase the habitat diversity and prevent downward incision (Pilloid et al. 2018, Scarmado and Wohl 2020). BDAs are an increasingly new feature that are being implemented in stream restoration techniques for their diminished cost, but these projects lack monitoring of their impacts on stream biota (Silverman 2019). Bouwes et al. (2016) observed higher density of rainbow trout and increased rainbow trout (*Oncorhynchus mykiss*) rearing habitat in BDA-impounded reaches compared to unimpounded reaches. This project's goals are to assess how BDA's affect stream ecosystem function on Crab Creek, WA.

Crab Creek is an approximately 225 km long creek that can be divided into 3 sections, upper, middle, and lower. The source of the creek is near Rearden, in Lincoln County, WA, USA (Figure 1). The stream flows south and west and is considered the Upper section of the creek until meeting with Moses Lake. The creek then flows through the middle and lower sections and eventually meets with the Columbia River about 5 miles south of Wanapum Dam. Crab Creek primarily flows through scab rock channels where much of the riparian vegetation has been removed for agricultural and cattle use. This has caused significant increased silt transportation and stream channel incision (KWA Ecological Sciences 2004).

In 2019, the U.S. Fish and Wildlife Service (USFWS), and Natural Resource Conservation Service (NRCS) placed 25 BDAs, on a section of private land (Brian Walker, USFWS, personal communication). The primary goal of placing the BDAs in the stream was to impound sediment and create a new floodplain at the currently incised stream channel (Brian Walker, USFWS, personal communication).

Since the installation of the BDAs in 2019, there has been little to no change in the geomorphology of the creek where the BDAs have been placed, and over the 10 past years Crab Creek has seen only modest flows from year to year, with peak flow events happening in year of 2014 and 2017 (Figure 1). Since the installation of the BDAs, Crab Creek has yet to have a significant flow event. Without significant flow events, little morphological change will happen to the river, thus leading to insignificant changes in habitat. Without significant changes to the habitat by this current restoration technique, there would be few changes to instream biota, as the given habitat is what ultimately determines what organisms are present or absent (Rabeni 2000). During flood events, sediment is transported downstream, there is an increase in bed scour, and stream beds have the possibility to move or rearrange. During these flow events, BDAs slow water velocity, and can cause sediment accumulation upstream of the BDA (Orr et al. 2020).

Objectives

1. Determine the effect of BDA installation on nutrient retention.
2. Measure effects of BDAs on drift and benthic macroinvertebrate assemblages.
3. Survey fish population and determine any differences in community structure associated with the placement of the BDA's.

Hypotheses:

Due to the increase of habitat heterogeneity, and increase of fish biodiversity caused by natural beaver dams, I expect to see an increase in the fish abundance in the BDA reach when compared to the control reaches. With stream velocity slowing through the BDA reach causing increased sediment deposition and a greater interaction between nutrients and instream biota, I expect to see an increase in the nutrient retention in the BDA reach when compared to the 3 control reaches. As water velocity is slowed through the BDA reach, I expect to see a decrease in drifting macroinvertebrate density in the BDA reach compared to the 3 control reaches. Driven primarily by the lentic habitat, and sediment deposition, I expect the benthic macroinvertebrate metrics (Table 1) to differ significantly in the BDA reach. Specifically, richness to decrease, Ephemeroptera, Plecoptera, Trichoptera richness to decrease, % Chironomidae to increase, % filterers to decrease, % collector-gatherers to increase, total chironomids to increase, total abundance to increase, biomass to increase, % burrowers to increase, the number of crayfish to increase, total Sphaeriidae to increase, and amphipods to increase.

Methods

Study Sites

Sampling sites on Crab Creek consisted of 3 control reaches and 1 treatment reach. The 3 control reaches were Tokio-Harrington (TH) (most downstream control reach, Figure 2), upstream of Canby Bridge (CB) (directly below the BDA reach), and downstream of Bluestem Bridge Road (BS) (immediately upstream of the BDA reach) (Figure 3). The BDA reach is the only treatment site of this study. Each of the study reaches were 1km long with the exceptions of the Canby Bridge reach which was 800m long and the BDA reach that was 975m long. Canby Bridge was truncated due to spatial limitations between the bridge and the BDA reach. The BDA reach was slightly truncated to just contain area within the BDAs with BDA buffers on both the lower and upper end of the reach.

The most spatially different reach from the BDA reach is the TH reach. The TH reach differs greatly in morphology and land use. The TH reach is located on public land owned by the Bureau of Land Management. This land is used by local outdoor enthusiasts, and cattle is allowed to graze on this section of public land. Crab Creek in this section lacks the stream incision that is seen on the upper treatment reach of the river (BDA, CB, and BS). This allows this section of Crab Creek to reach bank full and create flood plains. This section of stream also meanders and braids in more section, whereas the BDA, CB, and BS reaches are single channels. The BDA, CB, and BS reaches are located on a conservation easement. This conservation easement is located on a section of private land where the owners primarily use this for agriculture.

Sampling Timeline

Both drift and benthic macroinvertebrate sampling was completed in September of 2020. Nutrient sampling began September 2020 and continued through April 2021. Fish sampling took place October – November 2020.

Fish Sampling

To sample the fish population, a Smith Root (model #: LR20B) backpack fisher was employed. This method of sampling was approved by Eastern Washington University's Institutional Animal Care and Use Committee (IAUCAC). Permits were obtained prior to sampling from Washington Department of Fish and Wildlife (WDFW permit #: SPRUELL 20-043) for electroshocking on Crab Creek.

Each of the four study reaches had three 100 m, non-overlapping reaches selected by random number generator, with the exception of the Canby Bridge reach where the depth of the creek in some portions was too deep for backpack electrofishing. Starting from the most downstream sample in each reach, the backpack shocker was turned on its lowest setting and the current was adjusted until high enough to collect fish. The fish affected by the current were netted and placed into a container. The fish were then processed immediately to minimize stress on the fish. Each fish was identified to species and its total length was measured to the nearest mm then released back into the site from which it was collected. After completing each 100m reach, the shock time in seconds was recorded to calculate catch per unit effort (CPUE) for each individual sample.

Nutrient Sampling

The first nutrient sampling event (September 2020) comprised 6 nutrient sampling locations spaced 200 m apart within each of the four reaches. These samples allowed me to assess variability along each stream reach during low flow conditions, including whether there are localized nutrient sources and sinks within each reach. Each of the six sampling locations in each of the four reaches included three unfiltered and three filtered samples. In the successive months following September, October 2020 through April 2021, I only sampled nutrients at the most downstream and upstream points of each of the four study reaches. The reduction of sampling points was necessary to allow for efficient sampling of all sites during winter conditions. Water samples were placed into a cooler and transported to the lab and frozen until analyzed. Water samples were analyzed for nitrate, ammonium, orthophosphate, total nitrogen, and total phosphate using the Alpkem 3 flow analyzer, with persulfate digestion for total N and P (OIA 2009 a, b, c, Patton and Kryskalla 2003).

At each sampling site and at each sampling event, temperature (°C), dissolved oxygen (mg/L), pH, and conductivity (mS/cm^3) was measured at the upstream end of the reach using a calibrated YSI 556 MPS probe. Stream discharge was measured in each reach during September 2020 using the X-sectional area method (Hauer and Lamberti 2006).

Benthic Macroinvertebrate Sampling

Benthic macroinvertebrate sampling was completed during the month of September 2020. Twelve samples were collected from each study reach. Random numbers were used select specific points (distances upstream) for benthic sampling within each of the four reaches. Benthic macroinvertebrate sampling locations were alternated between left bank and right bank. Benthic macroinvertebrate sampling depths were no greater than 60 cm.

Benthic invertebrates were sampled using a Surber sampler (1ft^2 (~0.093m^2) sample area) with an attached 500 μm mesh size net. During sampling, the substrate was disturbed up to 10 cm for 3 minutes. The substrate was characterized according to the Wentworth (Wentworth 1941) scale at each of the 12 sampling locations in each of the 4 reaches. Collected invertebrates were placed into a labeled sample jars filled with 95% ethanol (Vanzol).

Drift macroinvertebrate sampling

Drifting macroinvertebrates were sampled with a 363 μm mesh size net. A random number generator was used to create 6 sampling locations within each of the four reaches, for a total of 24 samples. Rebar posts were driven into the substrate and were used to secure the drift nets in the thalweg of Crab Creek. Up to 3 drift nets were stacked until protruding from the surface of the water to capture any macroinvertebrates in the water column. Drift was collected for 30 minutes. Material and macroinvertebrates captured were removed and placed into a labelled sample jar that contained 95% ethanol (Vanzol). Water velocity through the nets was measured during each sampling event and drifting macroinvertebrate density was normalized by volume of water passing through the nets during the 30-minute sampling interval.

Macroinvertebrate Laboratory Analysis

Macroinvertebrate samples were stored in Vanzol until further analysis. Each drift macroinvertebrate sample was sorted under a dissecting microscope at 10x magnification. For benthic macroinvertebrates, samples required subsampling for efficient counting and identification. Each sample was divided into multiple square gridded petri dishes, random grid sections were selected, and all invertebrates present within selected sections were counted. A minimum of 500 invertebrates or 3 subsamples with an approximate area of 100 cm^2 each were processed for each sample. This material was sorted under 10x magnification to separate the macroinvertebrates from the particulate matter.

Macroinvertebrates were identified to the lowest practical taxon using the Plotnikoff and Wiseman (1996) guide for taxonomic resolution. The primary taxonomic key used for macroinvertebrate identification was Merritt et al. (2019). For a given taxon, individuals were be measured to the nearest 0.1mm. The first 25 individuals per site were measured for each taxon. If fewer than 25 individuals of the taxon were collected from the site, then all individuals were measured. Literature-based length/weight regressions were used to calculate biomass of each individual of each taxon (Benke et al. 1999, Ganiher 1997, Hodar 1996, Rogers et al. 1977, Sabo et al. 2002, Sample et al. 1993, Schoener 1980)).

Statistical Analysis

The statistical analysis used to test fish community composition and benthic macroinvertebrates was a 1-way ANOVA. The independent variable for both fish community composition and benthic macroinvertebrate was reach (BDA, CB, TH, or BS). Prior to ANOVA, the data were tested for normality and homogeneity of variance of the dependent variables. All fish community composition metrics initially failed the assumptions for the 1-Way ANOVA and were natural log transformed to meet the assumptions of the ANOVA. For benthic macroinvertebrate assemblages, some dependent variables (Amphipods, Crayfish, Biomass, Total Chironomidae, EPT Richness) were transformed using natural logs, and others (Percent Chironomidae, Percent Filterers, Percent Burrowers, Percent Collector/Gatherers), were transformed using arcsin square root transformation to meet the assumptions of the ANOVA. Both fish and benthic macroinvertebrate ANOVAs were followed by a post hoc-Tukey test to determine the effect of the BDA's. To compare substrate composition in each of the four reaches, A Fisher's exact test was used with the reach as the independent variables and substrate the dependent variable.

Drifting macroinvertebrates metrics were tested using a Kruskal-Wallis test followed by a post hoc-Dunns test using the Benjamini-Hochberg method (Benjamini and Hochberg 1995). This test was used as the data for the drift macroinvertebrates did not follow the assumptions of an ANOVA and any transformations performed on the data still failed the assumptions of an ANOVA.

I used a 2-way ANOVA with site and year as independent variables to detect changes in benthic macroinvertebrate assemblages that may have occurred since previous macroinvertebrate sampling (Klinzing, 2011). Data were tested for the assumptions of the ANOVA and some dependent variables (Richness, EPT Richness, Total Chironomidae, Amphipods, Crayfish, Sphaeriidae) were natural log transformed and other variables (Percent Chironomidae, Percent Filterers, Percent Collector Gatherers, Percent Burrowers) were transformed using an arcsin square root transformation to meet the assumptions of the ANOVA. The 2-way ANOVA was followed by a post hoc estimated marginal means test to detect any changes between reach and year.

To determine any significant changes in nutrient retention from the upstream sampling point to the downstream sampling point, I used a repeated measures ANOVA, with the independent variables being the 4 reaches (BDA, CB, TH, BS) and the dependent variables were ammonium, nitrate, phosphate, Total N, and Total P. Each analyte tested using the repeated measures ANOVA and data was tested for normality and homogeneity of variance. Each analyte was natural log transformed and retested for the assumptions of the ANOVA. The repeated measures ANOVA was followed by post hoc estimated marginal means test to determine the effect of the BDA's reach on nutrient retention.

Results

Fish community composition

In total, 6 fish species were identified among the 4 reaches: rainbow trout (*Oncorhynchus mykiss*), speckled dace (*Rhinichthys osculus*), brown trout (*Salmo trutta*), brook trout (*Salvelinus fontinalis*), bridge lip sucker (*Catostomus columbianus*), and redside shiner (*Richardsonius balteatus)*. Total fish abundance (CPUE) was lower in the TH reach compared to the BDA and BS reaches; the other reaches did not differ significantly in fish CPUE (Figure 4., Tables 3 & 4). I also compared abundance of individual species among the reaches. Rainbow trout were more abundant in the BS than the TH reach; no significant differences were detected between the other reaches (Figure 5., Table 4). Significantly more redside shiners were collected in the BDA reach when compared to the rest of the reaches, but no differences were detected between the other 3 reaches (Figure 6., Tables 3 & 4). Neither bridge lip sucker abundance or speckled dace abundance varied significantly among sites. No statistical tests were performed on brown trout or brook trout abundance as the densities of these fish were very low and they were not present in some reaches. The Shannon-wiener diversity of fishes also did not vary significantly among sites.

Nutrient Analysis

To determine potential sources or sinks of nutrients within reaches, nutrients I sampled water every 200m within each reach in September of 2020 (Figure 7-11). The most variable nutrient concentrations occurred in the CB reach. Concentrations of total P, total N, phosphate, and ammonium varied greatly throughout the reach. The BS reach also had variation in the concentrations of ammonium and phosphate within the reach. The nutrient concentrations for the TH reach did not vary greatly, and were consistent throughout the reach for all the analytes tested. There was little variation in the nitrate concentration within the CB reach. The BS reach had little variation in total N and total P concentrations throughout the reach. The BDA reach had little variation in for total N and phosphate concentrations.

Using all months' data, comparisons were made from the most upstream sampling point to the most downstream sampling point for all nutrients tested. Ammonium increased significantly from upstream to downstream in the BS and CB reaches (Figure 7). Nitrate tended to decrease from upstream to downstream in the BS and BDA reaches (Figure 8). The BS reach saw an increase in the phosphate concentration within the reach (Figure 9). The CB reach decreased in the amount of total N (Figure 10) and total P, while the BDA reach increased in the amount of total P, see Figure 11.

Ammonium concentrates were consistently higher at the downstream end of the BS reach compared to the upstream end (Figure 12., Table 5 & 6). Concentrations of ammonium did not differ between the upstream and downstream ends of the other reaches. The nitrate concentrate was consistently higher at the downstream sampling point compared to the upstream end of the BS reach (Figure 13., Table 5 & 6). Concentrations of nitrate did not differ between the upstream and downstream end of the other reaches. There were no differences in concentrations between the upstream and downstream sampling points of phosphate, total N, and total P, see Tables 5 and 6. When testing total P in the laboratory, a contaminate was present in the testing solution and months of November and December were removed from the statistical analysis.

Benthic macroinvertebrate assemblages

The benthic macroinvertebrate assemblages tested are summarized in Table 1. In total, 16,819 macroinvertebrates were identified to the lowest practical taxon. Macroinvertebrate taxa richness was higher in the CB reach than the BDA reach (Figure 14., Table 8). Macroinvertebrate total abundance was higher in the BDA and CB reach when compared to the TH reach (Figure 15., Table 9). The Biomass of macroinvertebrates was higher in the BDA reach when compared to the TH reach (Figure 19., Table 9). Macroinvertebrate taxa EPT richness was significantly less in the TH reach when compared to the other reaches (Figure 16., Table 8). The total Chironomid abundance was lower in the TH reach and higher in the other reaches (Figure 17., Table 8). The percentage of Chironomids in each sample was higher in the BDA reach when compared to the TH reach (Figure18., Table 9). The TH reach had less amphipods present when compared to the other reaches, and the BDA reach had significantly more amphipods present than the CB reach (Figure 20., Table 9). There were more Sphaeriidae present in the BS and CB reach than in the TH reach (Figure 21., Table 9). The percent functional feeding collector-gatherers and percent habit burrowers increased in the BDA reach when compared to the TH and CB reaches (Figures 22 & 23., Table 9). There were no differences in the number of crayfish present or the relative abundance of the functional feeding group filterers (Table 8).

Drift Macroinvertebrates

The total density of macroinvertebrates was compared among the 4 reaches as well as densities of the following invertebrate groups: macroinvertebrate density, Oligochaetes, *Tricorythodes* mayfly nymphs, *Gammarus* amphipods, Baetidae mayfly nymphs, Ephemeroptera adults, and Nematoceran Diptera adults. Drifting macroinvertebrate density increased in the BS and CB reach when compared to the TH reach (Figure 27., Table 11). The density of drifting Oligochaetes increased in the BS and CB reach when compared to the TH reach (Figure 24., Table 11). The BS reach had more drifting *Tricorythodes* nymphs present when compared to the BDA reach (Figure 25., Table 11). The CB reach had more drifting *Gammarus* when compared to the TH reach (Figure 26., Table 11). There were no differences among the 4 reaches when comparing densities of drifting Baetidae nymphs, Ephemeroptera adults, or Nematocera larvae (Table 10).

Comparison with previous invertebrate communities

I compared the following components of the macroinvertebrate assemblage between 2009 and 2020 for the BDA and TH reach: taxon richness, EPT richness, Sphaeriidae abundance, Chironomidae abundance, percent Chironomidae, amphipod abundance, crayfish abundance, and relative abundances of filterers, percent collector – gatherers and burrowers. The taxon richness was higher in 2009 compared to 2020 in both the TH and BDA reach (Figure 28., Table 13). The EPT richness was also higher in 2009 when compared to 2020 (Figure 29., Table 13). Chironomidae abundance increased from 2009 to 2020 for both reaches (Figure 30., Table 13), as did the relative abundance of Chironomids (Figure 31., Table 13). The relative abundance of the function feeding group collector-gatherers increased from 2009 to 2020 in the BDA reach (Figure 32., Table 13), but no there were no differences in the TH reach from 2009 to 2020. The relative abundance of burrowers increased in the BDA reach from 2009 to 2020 (Figure 33., Table 13), and but changes were detected for the TH reach from 2009 to 2020.

Substrate Composition

The substrate at each benthic macroinvertebrate sampling point was characterized as either silt or greater than or equal to cobble on the Wentworth scale. These data were used to compare the relative abundance of these 2 substrate types among the 4 reaches. The substrate of the TH reach had significantly more cobble present at each benthic macroinvertebrate sampling site than the other reaches (Fisher's exact test, p = 5.666e-05, see Figure 34). When the TH reach was removed from the analysis, it there was no difference in substrate composition between CB, BDA, and BS reaches. A summary of the substrate characterization can be found in Table 15.

Physical stream measurements

The warmest water temperature for Crab Creek recorded during this study was during sampling was in the month of September 2020 and was around 14 °C. At each sampling time, the water temperature was similar for all four reaches (Figure 35). During the month of February 2021, the region had a period of substantially colder weather. During that sampling event, reaches TH and CB were frozen over with ice, while both the BDA and BS reach still had flowing water. Specific conductance values did not vary greatly from reach to reach during monthly sampling. The only variation in specific conductance values happened in the later months of sampling, March and April, where the TH reach deviated from the CB, BDA, and BS reach (Figure 36).

Discussion

This study examined the effects of beaver dam analogs on stream ecosystem function of Crab Creek, WA. These findings do suggest that BDA's impact stream ecosystem function. One of the most significant results of this study was the increased density of redside shiners present in the BDA reach. The two control reaches adjacent to the BDA reach, CB and BS, are channelized, and lack woody debris, whereas the TH reach is not channelized, but spatially distant from the treatment reach. The BDA placed woody debris back into the stream and accumulated aquatic vegetation and tumbleweeds (dead *Sisymbrium altissimum*, Broderius, unpublished observation). When backpack electrofishing, a significant portion of the redside shiners caught in this study was adjacent to a BDA. Redside shiners are in the minnow family, and prefer slow moving habitat with cover (Rodnick 1983). With the significant amount of redside shiners present near or in the BDA, the BDAs are most likely providing the preferred habitat of the Redside Shiner, which the CB and BS lack.

The substrate composition of the BDA, CB, and BS reach can give an insight to the lack of statistically significant benthic macroinvertebrate results when comparing the BDA reach to the control reaches immediately upstream and downstream. With the substrate between these reaches being primarily silt, the lack of changes in these benthic macroinvertebrate metrics is not surprising. Beaver impoundments accumulate silt (Orr et al. 2020) and an increase in siltation is an expected impact of BDAs. As silt was the dominant substrate throughout this stretch of Crab Creek, any increased siltation resulting from BDA installation may not have altered the invertebrate community. Burrowers were the dominant functional group in terms of substrate use, accounting for over 87% of the macroinvertebrates present in the BDA reach. In the adjacent control reaches (CB and BS) this functional habit group accounted for over 50% of the assemblage (Table 7).

Although few changes in the invertebrate community as a result of BDA installation were detected, there were significant changes over time between 2009 and 2020. The relative abundance of burrowers increased dramatically in the BDA reach between 2009 and 2020. This increase is largely attributable to increases in Chironomidae and Oligochaeta. Taxa richness and EPT richness decreased from 2009 to 2020. These changes in the primary functional habit where burrowers now dominate, and increase of 76% suggest that there has been a change in the substrate composition from 2009 – 2020. There could be influence of the BDAs on the functional habit burrowers as the TH reach did not see any significant changes in the percent burrowers from 2009 to 2020. However, the dominance of burrowers in the control reaches adjacent to the BDA reach (CB and BS) suggests the change from 2009 to 2020 is likely to have occurred over a larger landscape scale.

BDAs are a process-based stream restoration strategy that aims to use stream energy to affect the fluvial process (Ciotti et al. 2021). Floods events can rapidly reorganize the landscape by impounding sediment, creating new channels, and filling incised stream segments (Nash 2021). By altering sediment dynamics, BDAs have the potential to accumulate sediment behind dams and harvest sediment from eroding banks (Orr et al. 2020, Nash et al. 2021). However, these processes require significant changes to the stream profile and hydrology (Ciotti et al. 2021, Nash et al. 2021, and Wohl et al. 2015). The BDAs installed on Crab Creek have not experienced a significant flood event since installed, Figure 1. Thus, current effects of BDAs on nutrient transport, invertebrate or fish assemblages would be due to the direct physical presence of the wooden structures, likely without significant alteration of channel form. Without added stream energy, this type of process-based stream restoration may have very little effect on the successional process (Ciotti 2021). Since the physical parameters of the stream will drive what macroinvertebrates are present, it is not surprising that reaches with the same substrates present would not differ greatly from one another in macroinvertebrate communities (Rabeni 2020).

One of the major limitations of stream restoration strategies or projects, is that there can be a disconnect between the landscape scales of alteration and restoration (Booth et al. 2016, Wohl et al. 2015). Alterations made to these streams would have constraints between humans and landowners' activity on the land where watershed scale processes are a major factor on reach scale conditions (Boot et al. 2016). This could potentially be a limitation of this study where much of Crab Creek in still used for agriculture and the influence of the BDA reach is spatially considerably smaller than the watershed above the treatment reach.

Stream restoration techniques, in this case, are most likely limited by environmental factors that are outside human control, and these factors should be accounted for when evaluating the efficacy of a restoration technique (Nash et al 2021). While some effects could be immediate, for example the high density of redside shiners within the BDA reach, other factors such as macroinvertebrates and nutrient retention, could potentially take longer to develop (Booth et al. 2016).

It is important to know whether these stream restoration techniques effect stream ecosystem function. While this study found limited effects of BDAs on the biota and nutrient retention, future research should focus on the effects of macroinvertebrates and nutrient cycles in streams. It is up to the entity responsible for the stream restoration to use techniques that provide adequate restoration, and it is still unclear whether BDAs are as an effective restoration technique and if they have similar effects of natural beaver dams.

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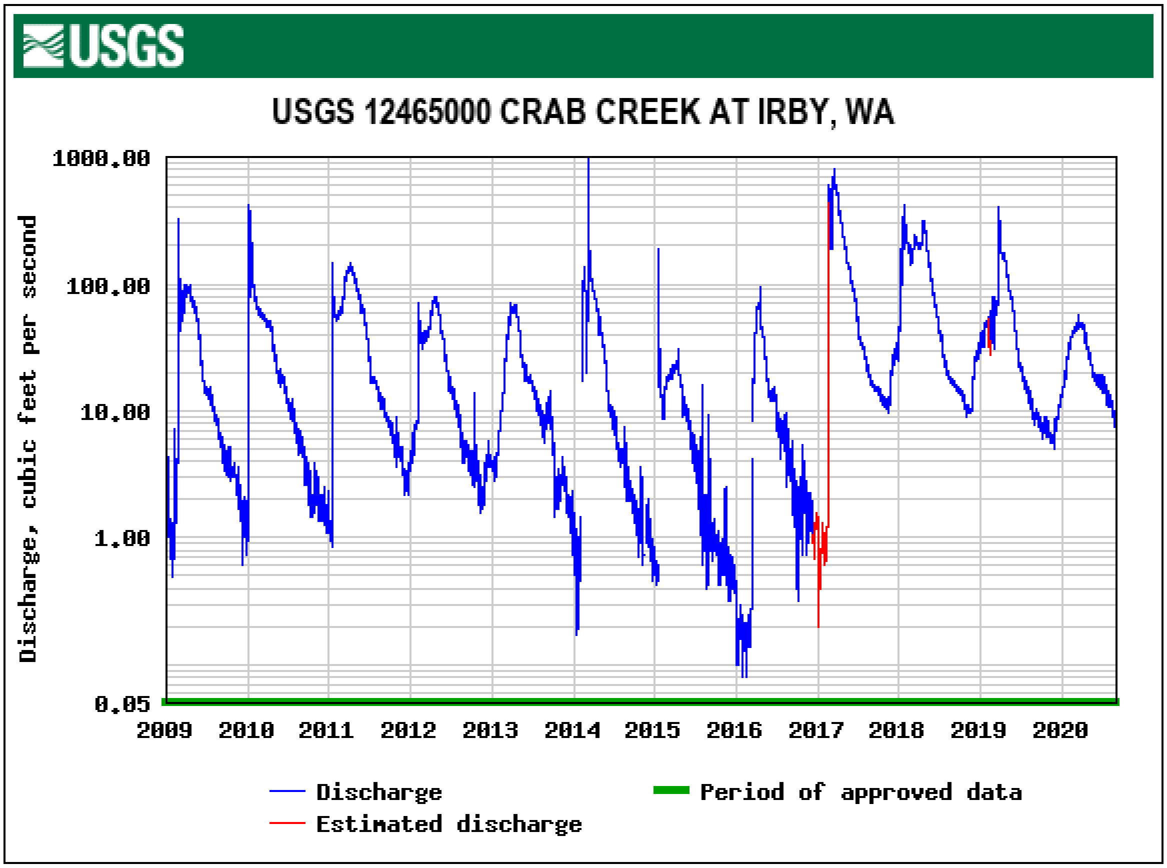

Figure 1. Crab Creek discharge information at USGS gaging station in Irby, WA.

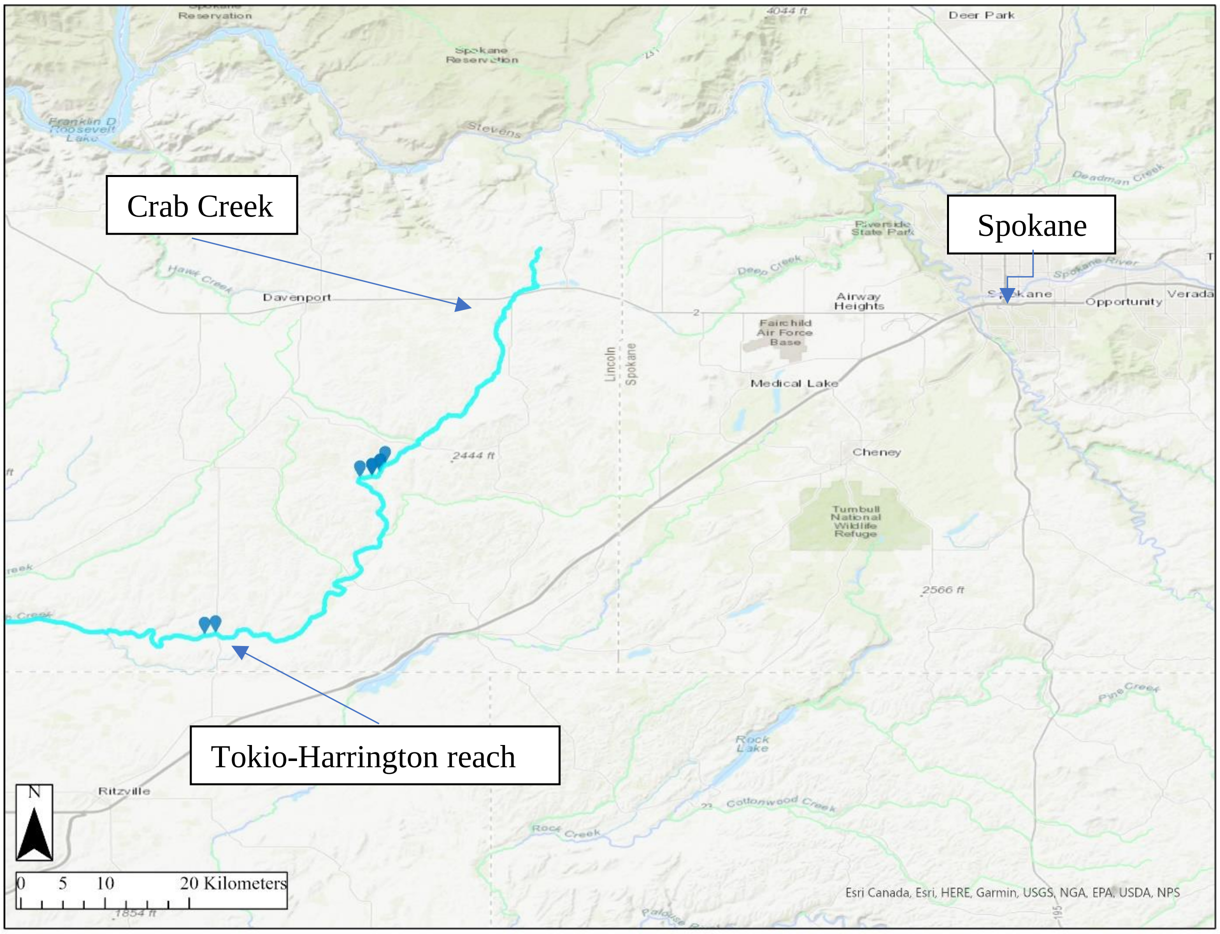

Figure 2. Overall map of study reaches on Crab Creek. Tokio-Harrington reach identified.

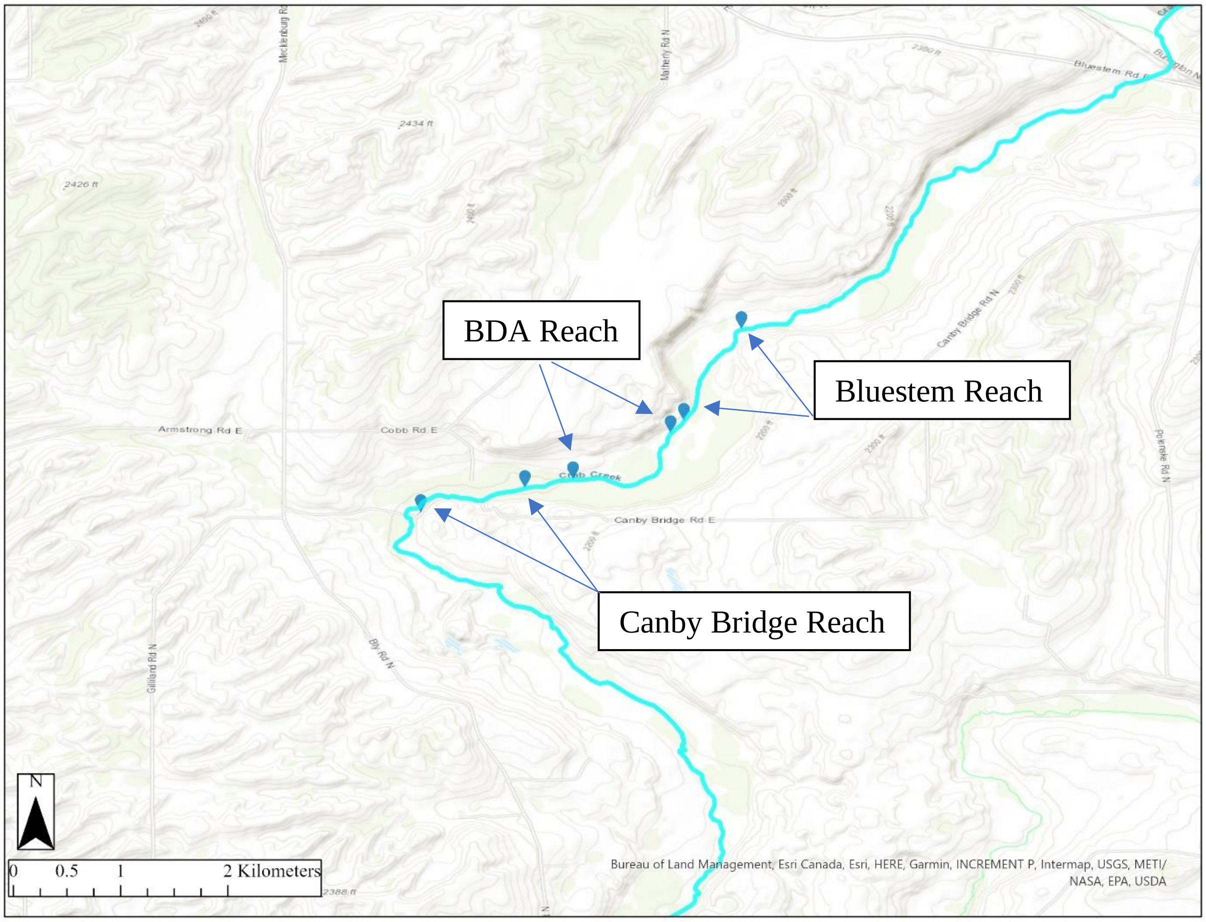

Figure 3. Map of study reaches on Crab Creek. Highlighted creek is Crab Creek.

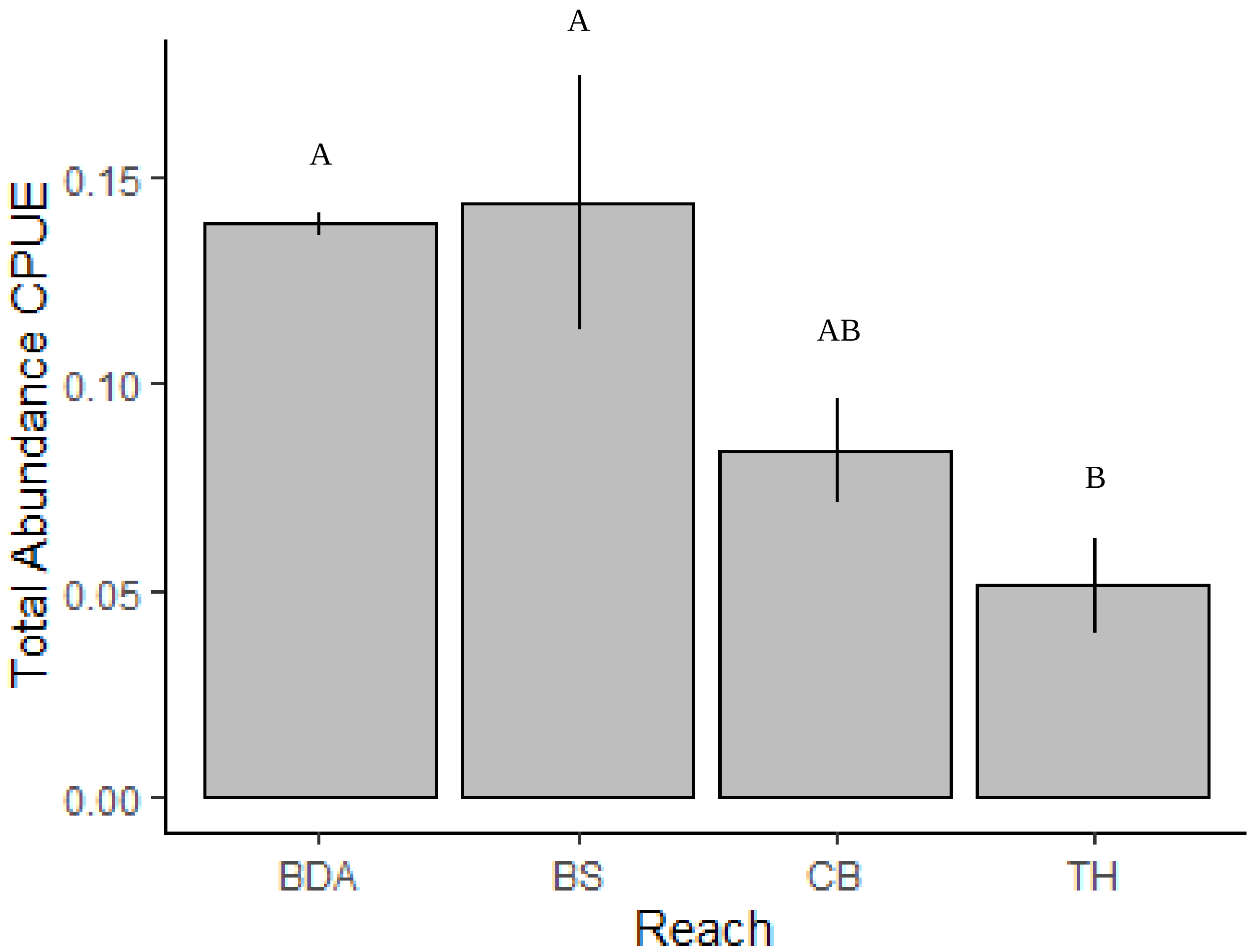

Figure 4. Mean (± se) of total fish abundance catch per unit effort between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

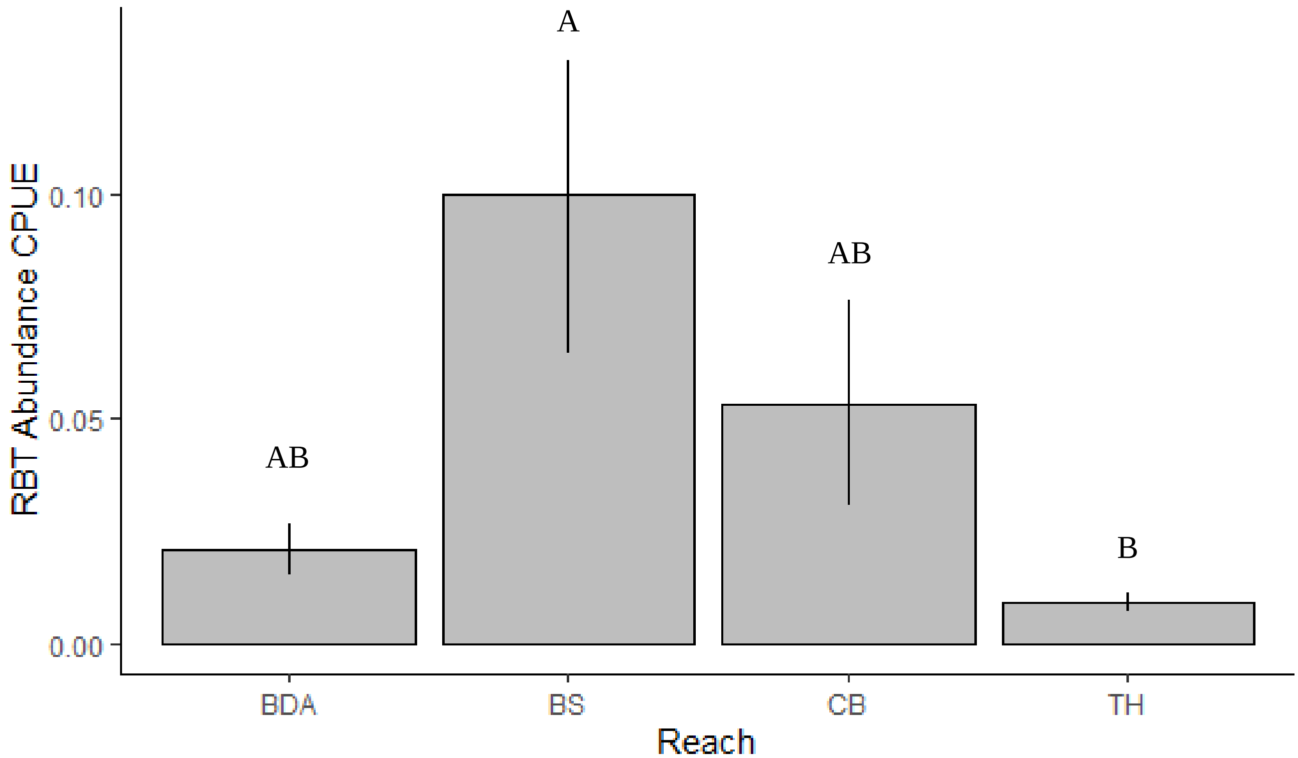

Figure 5. Mean (± se) of Rainbow Trout abundance catch per unit effort between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

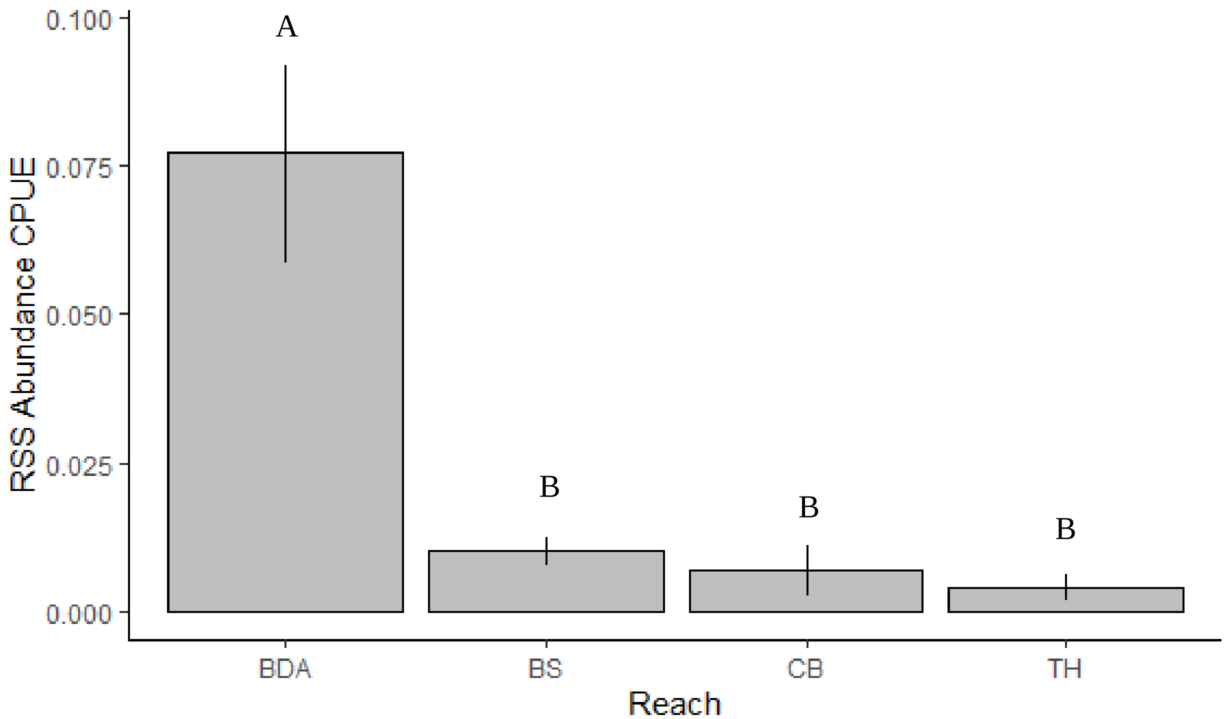

Figure 6. Mean (± se) of Redside Shiner abundance catch per unit effort between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A and B, A is statistically different from B.

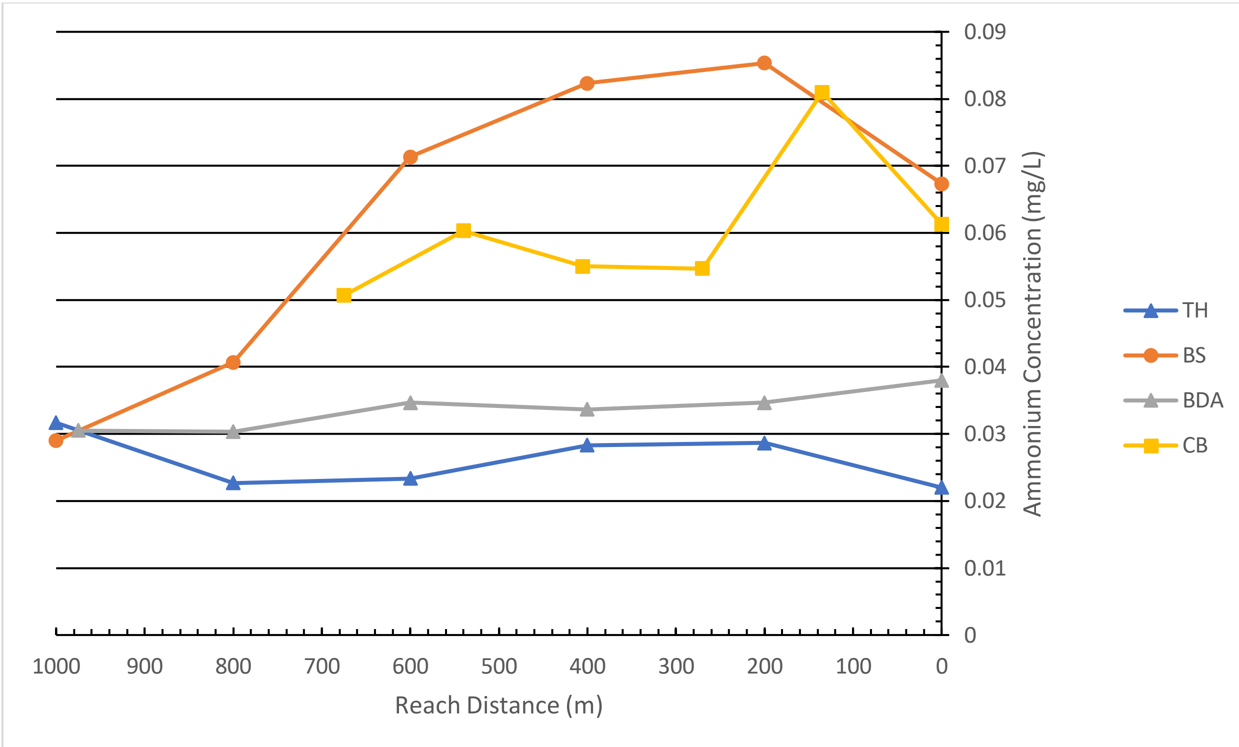

Figure 7. September sampling of ammonium concentrations. Reach distance 1000 is most upstream sampling point, reach distance 0 is most downstream sampling point.

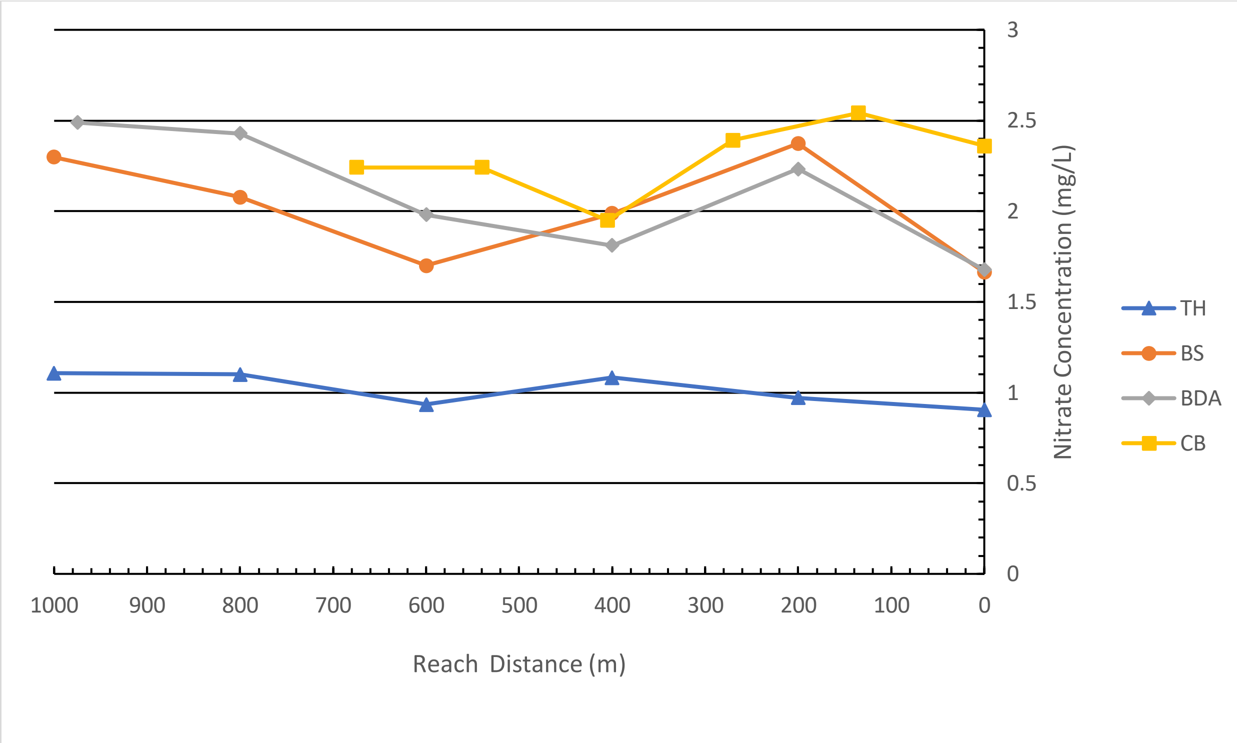

Figure 8. September sampling of nitrate concentrations. Reach distance 1000 is most upstream sampling point, reach distance 0 is most downstream sampling point.

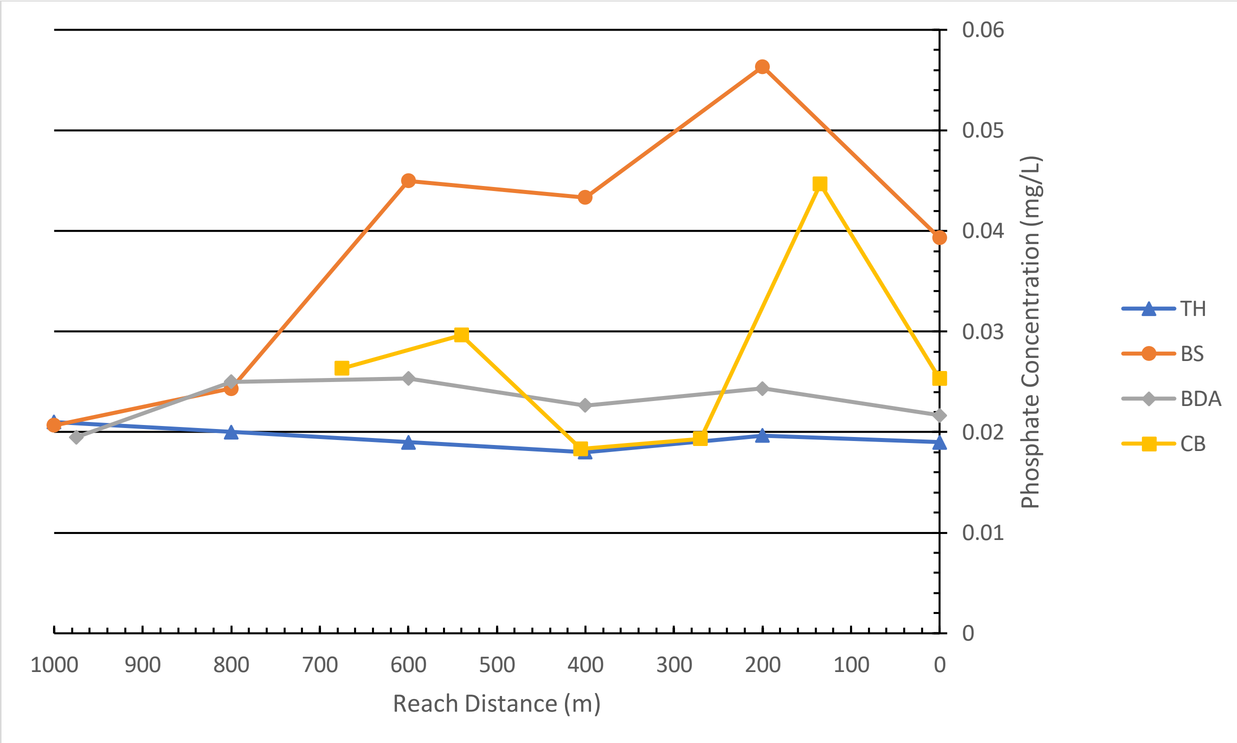

Figure 9. September sampling phosphate concentrations. Reach distance 1000 is most upstream sampling point, reach distance 0 is most downstream sampling point.

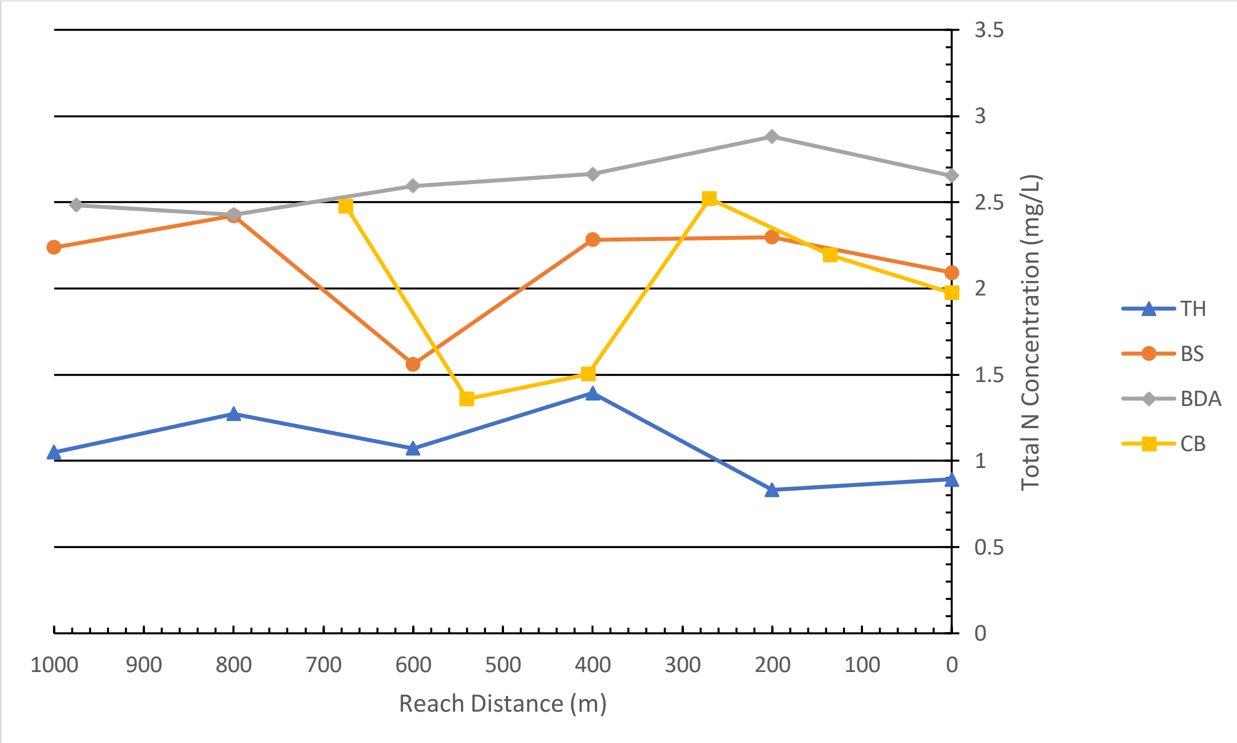

Figure 10. September sampling of total nitrogen concentrations. Reach distance 1000 is most upstream sampling point, reach distance 0 is most downstream sampling point.

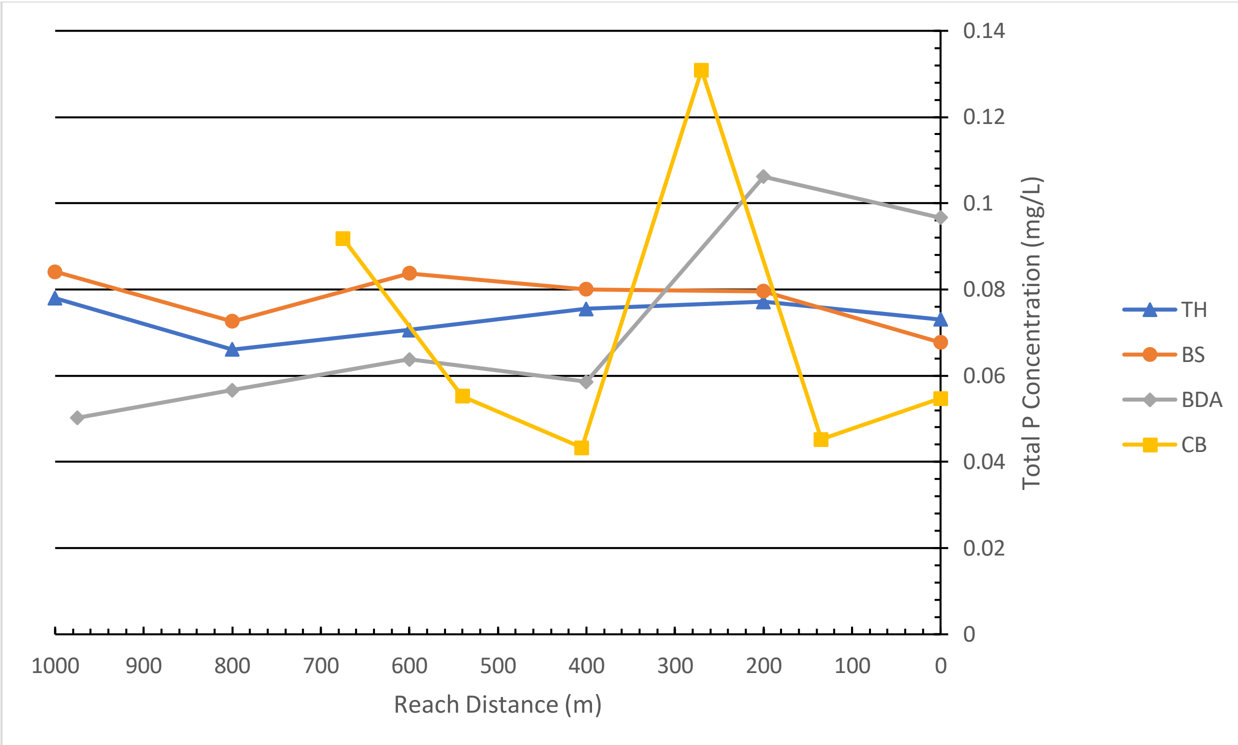

Figure 11. September sampling of total phosphorus concentrations. Reach distance 1000 is most upstream sampling point, reach distance 0 is most downstream sampling point.

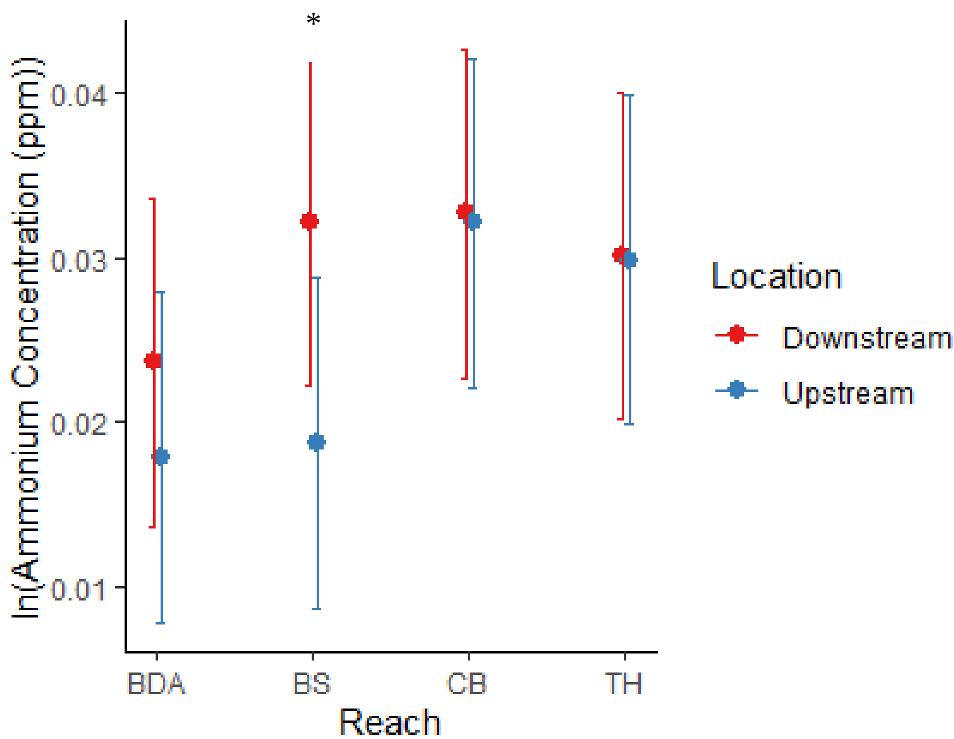

Figure 12. Model of ammonium nutrient retention between the 4 reaches. Error bars are 95% CI of model. Statistical significant ($p<0.05$) results are denoted with *.

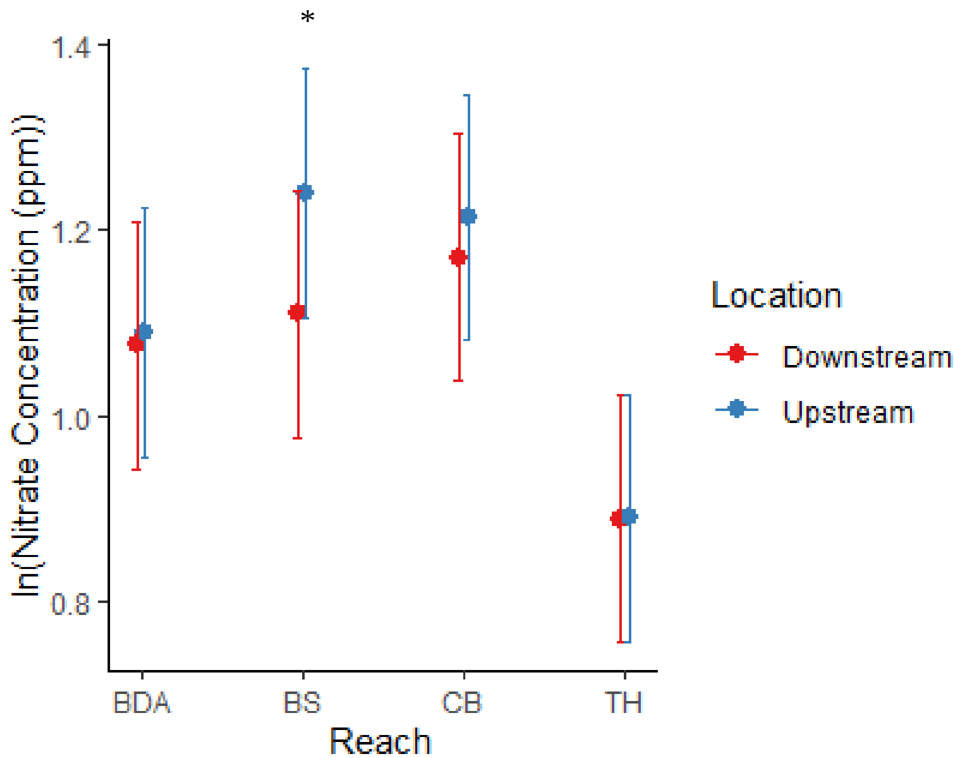

Figure 13. Model of nitrate nutrient retention between the 4 reaches. Error bars are 95% CI of model. Statistical significant (p<0.05) results are denoted with *.

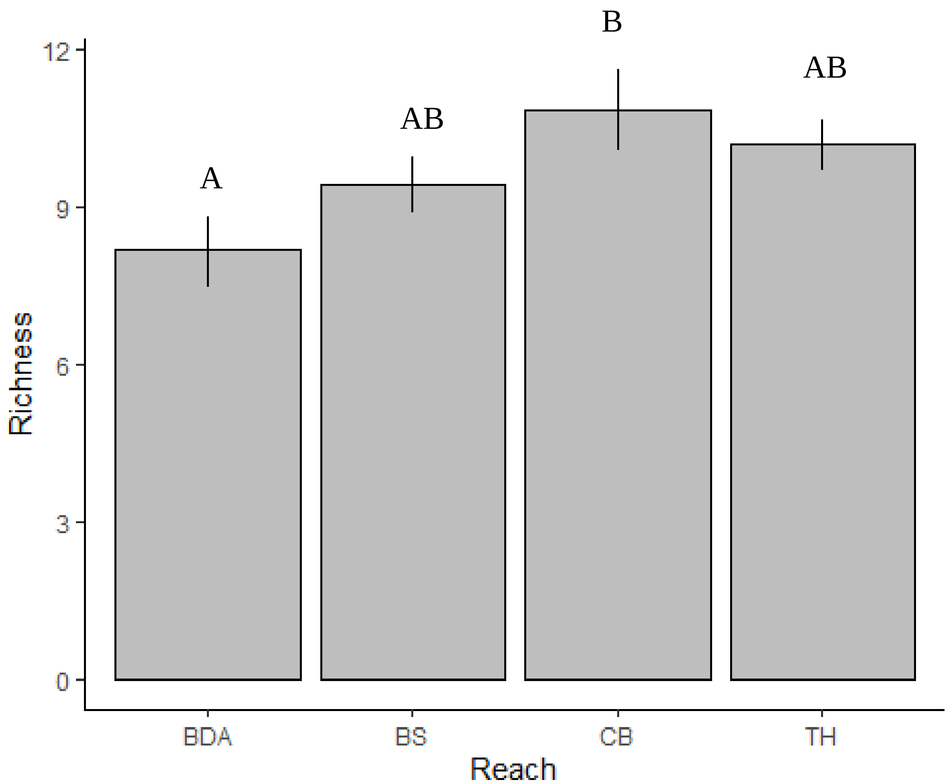

Figure 14. Mean (± se) of macroinvertebrate family richness between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

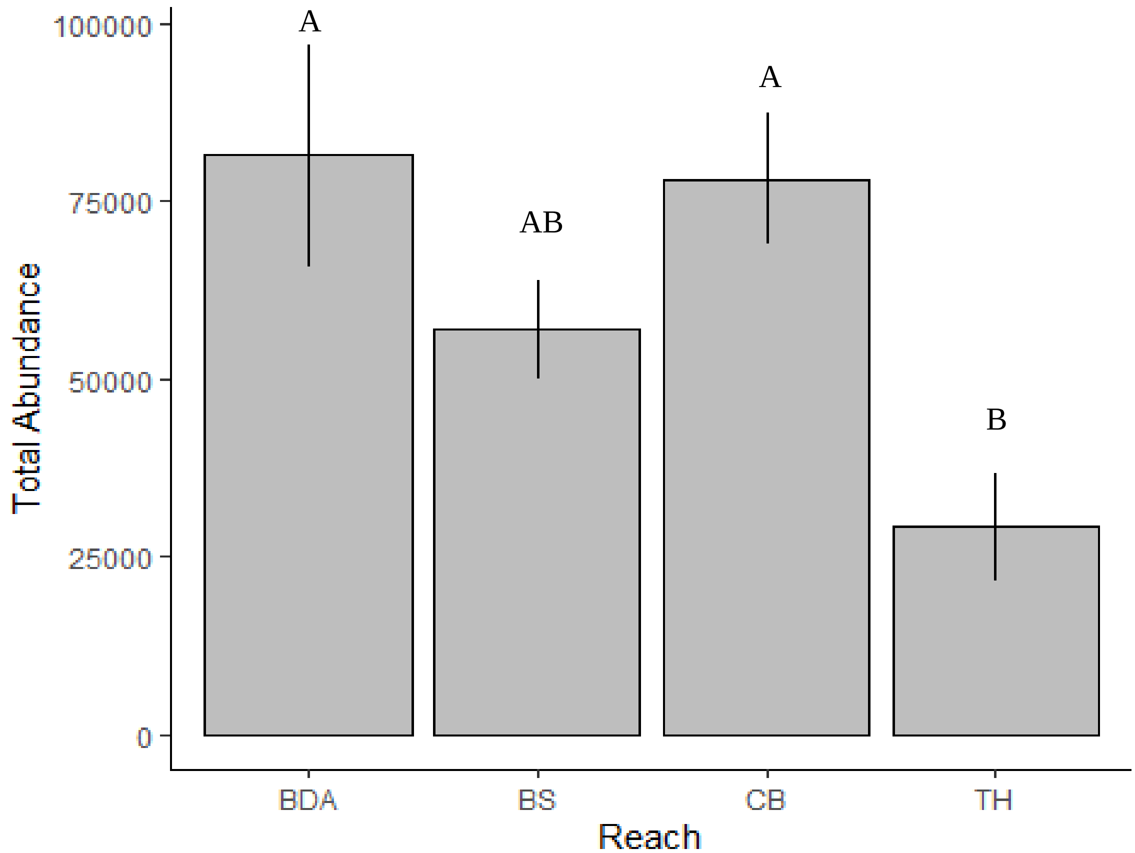

Figure 15. Mean (± se) of macroinvertebrate total abundance (# of individuals*m^{-2}) between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

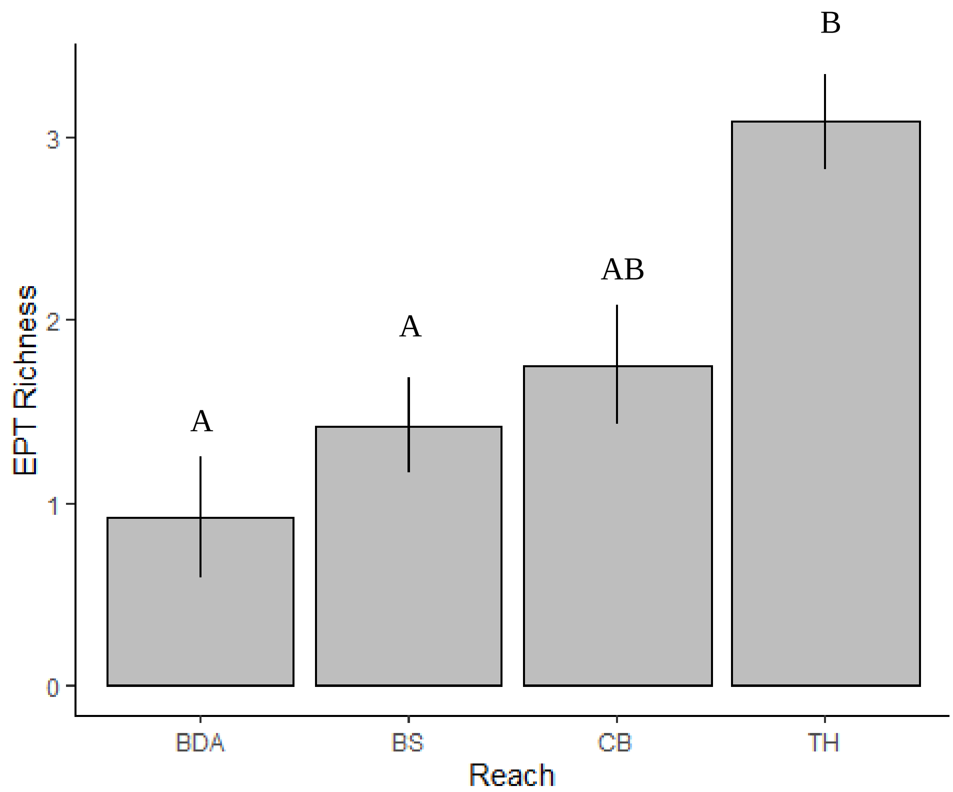

Figure 16. Mean (± se) of macroinvertebrate richness in the families Ephemeroptera, Plecoptera, and Trichoptera between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

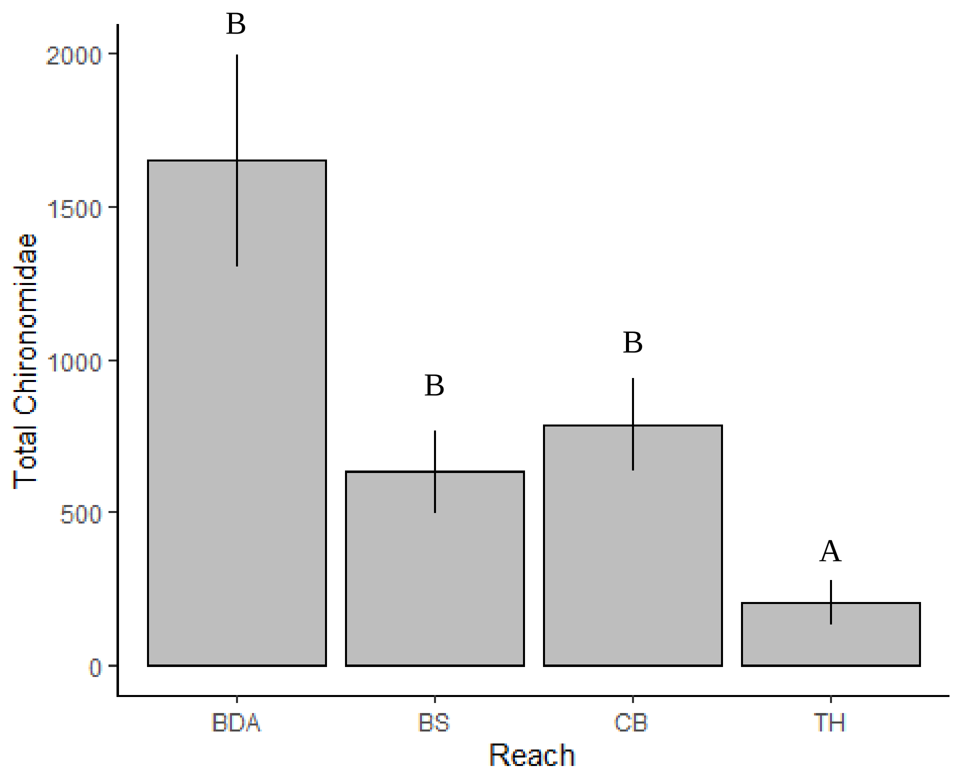

Figure 17. Mean (± se) of total Chironomidae between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A and B, A is statistically different from B.

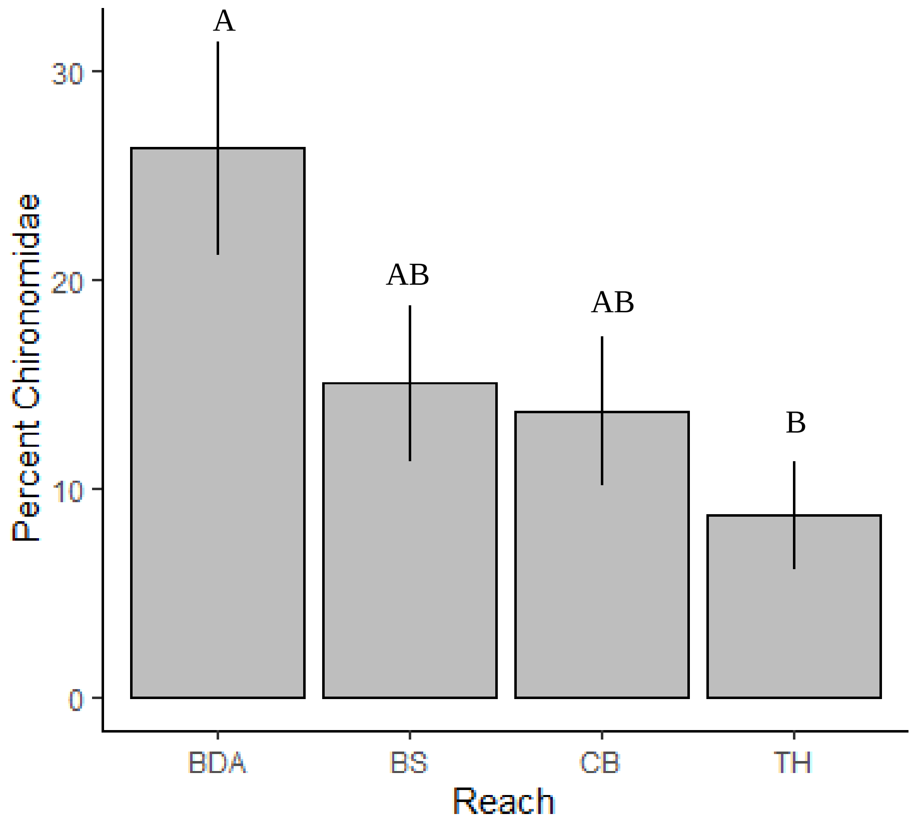

Figure 18. Mean (± se) of percent Chironomidae present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

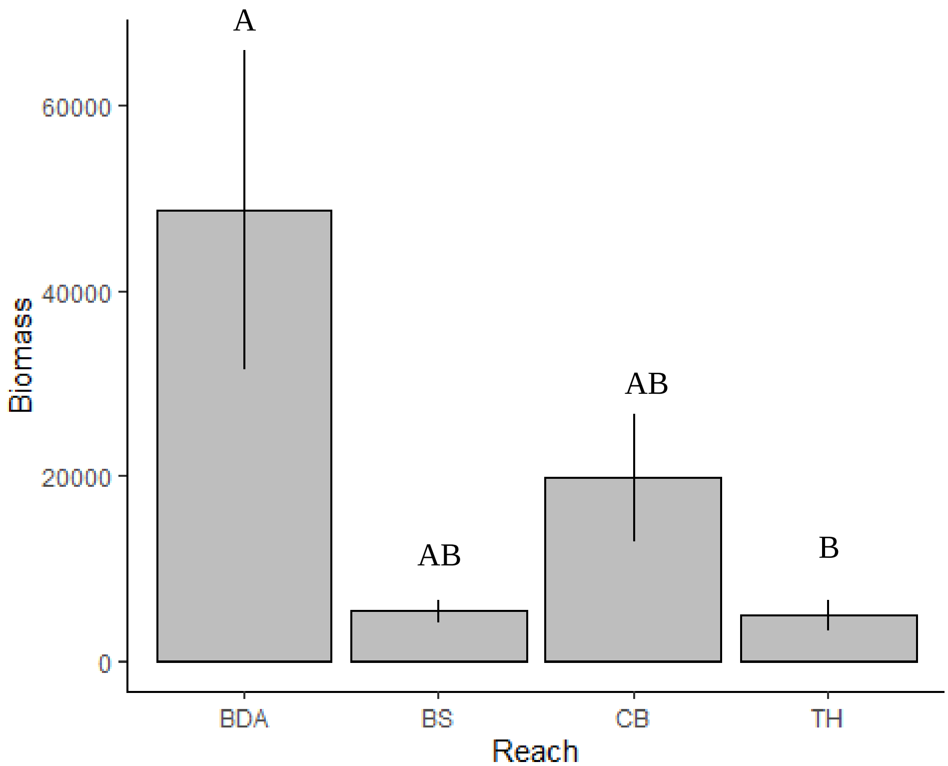

Figure 19. Mean (± se) of the Biomass (mg*m^{-2}) of macroinvertebrates present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

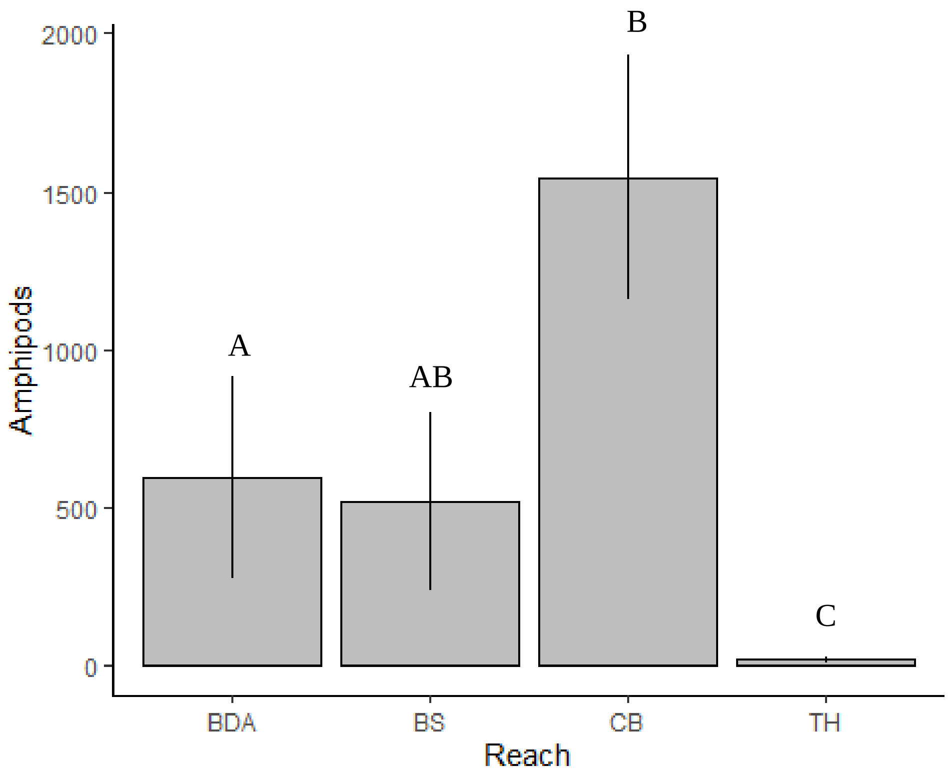

Figure 20. Mean (± se) of number of Amphipods present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

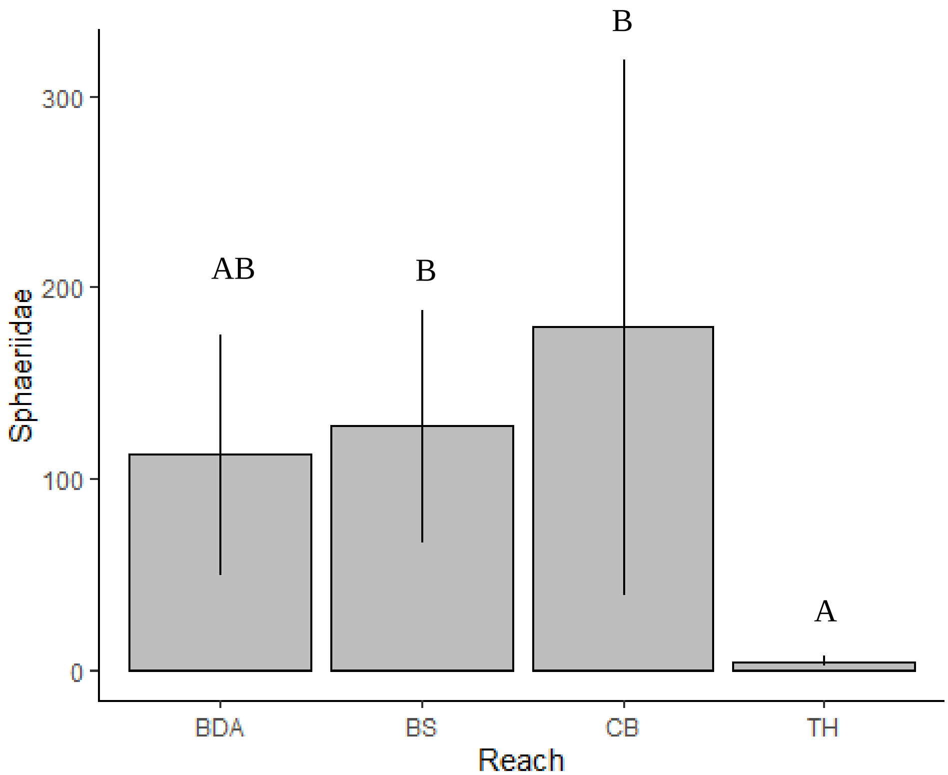

Figure 21. Mean (± se) of Sphaeriidae present between the 4 reaches. Significant impacts (p<0.05) are denoted with A, AB, and B. A is statistically different from B.

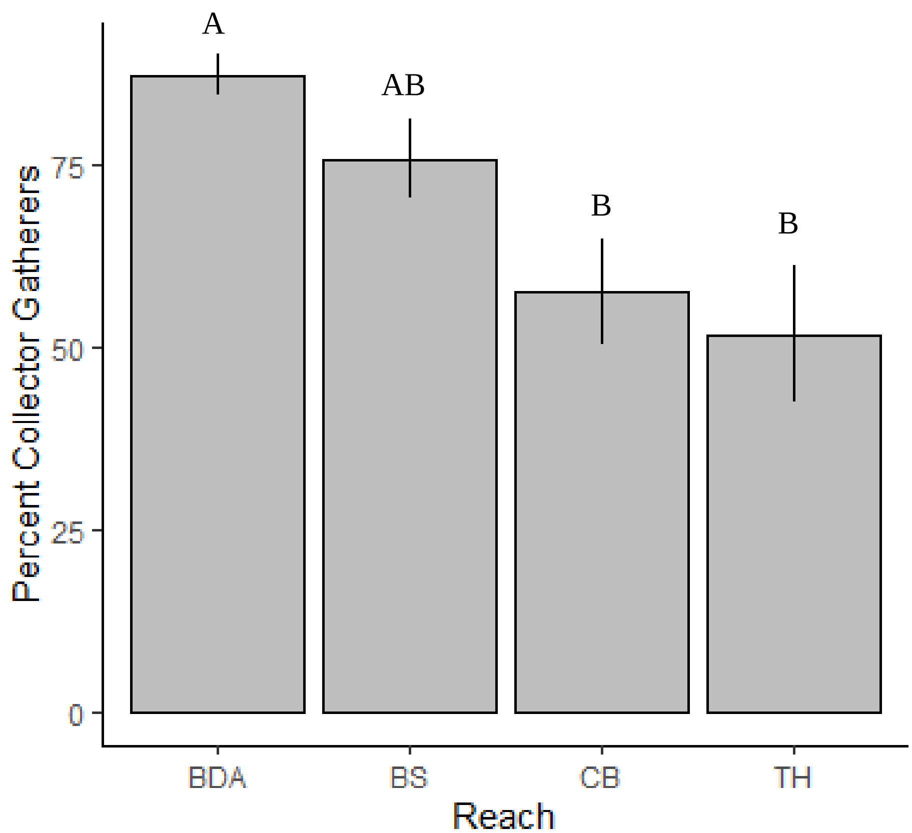

Figure 22. Mean (± se) of percent functional feeding group collector-gatherers present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

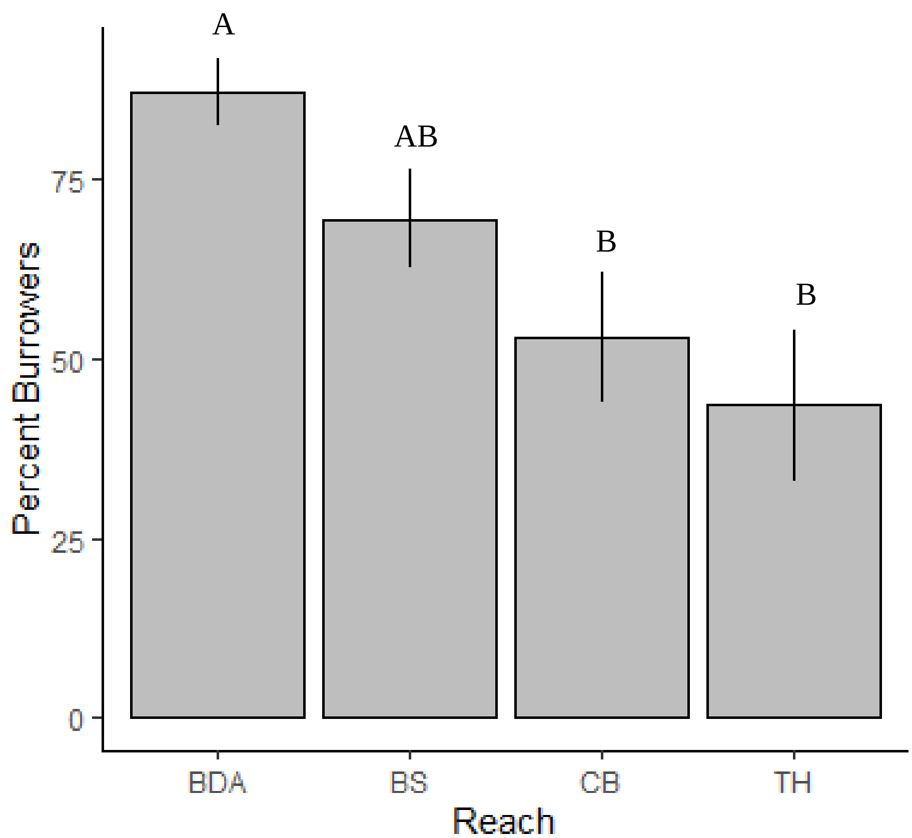

Figure 23. Mean (± se) of percent functional habit group burrowers present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

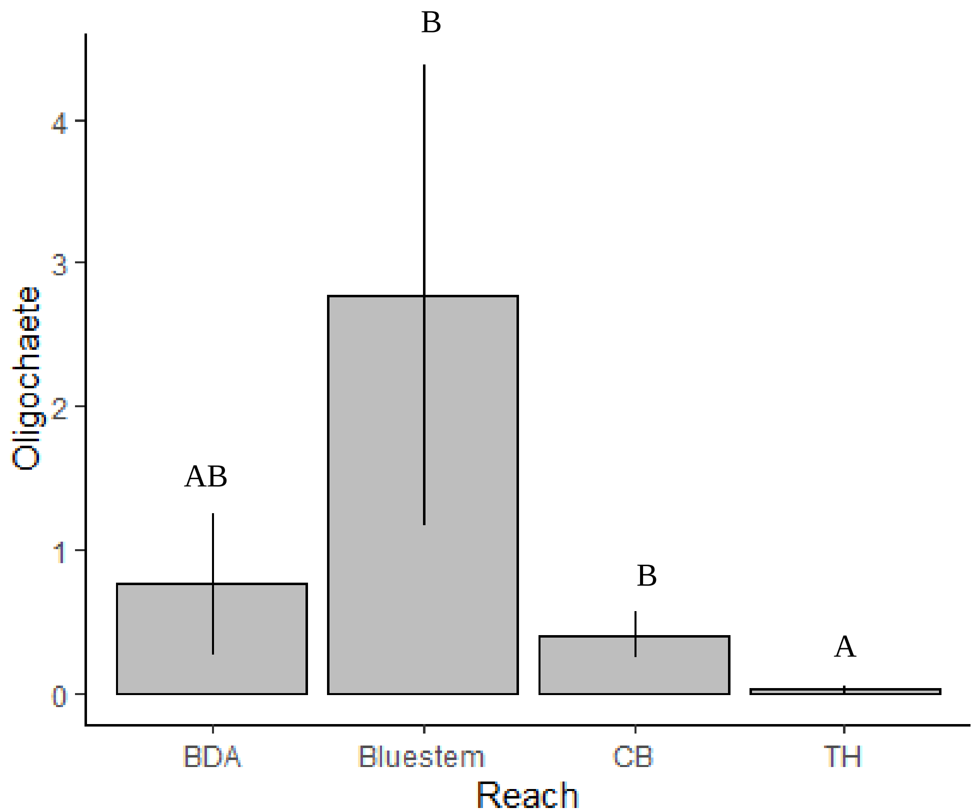

Figure 24. Mean (± se) of drifting Oligochaetes present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

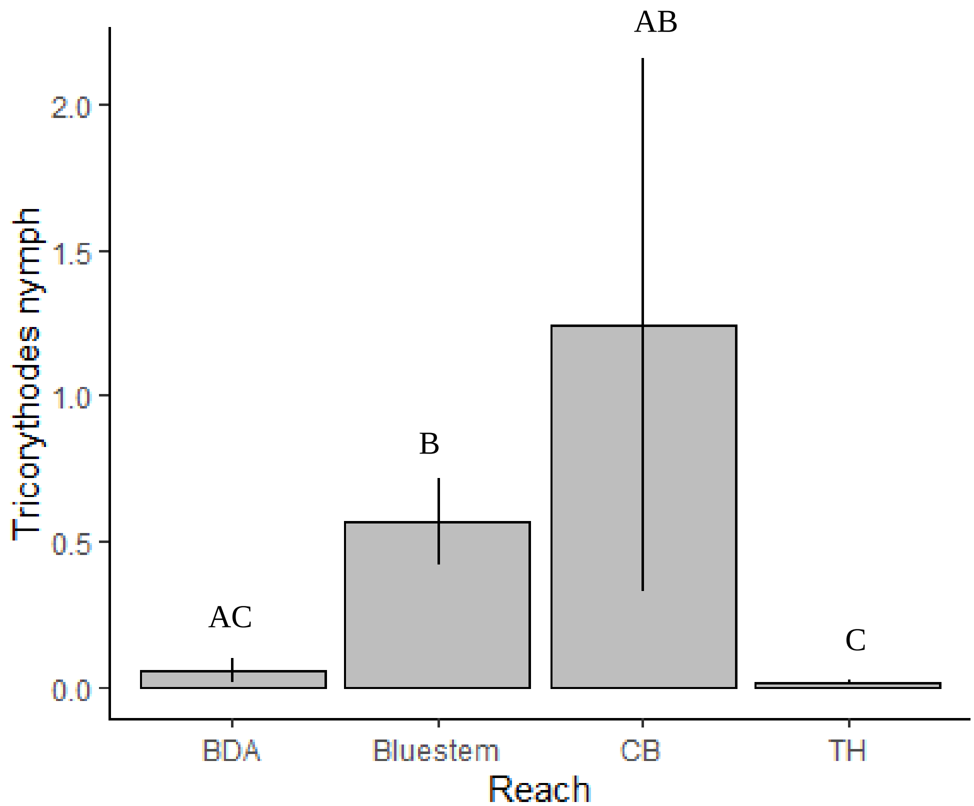

Figure 25. Mean (± se) of drifting Tricorythodes present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

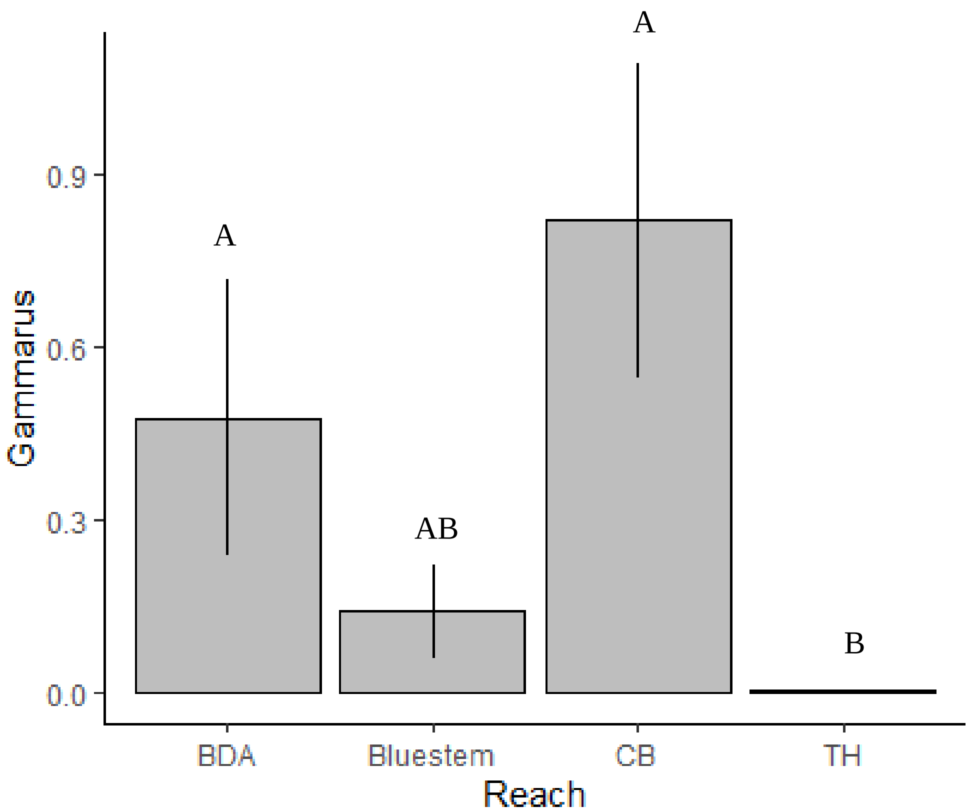

Figure 26. Mean (± se) of drifting Gammarus present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

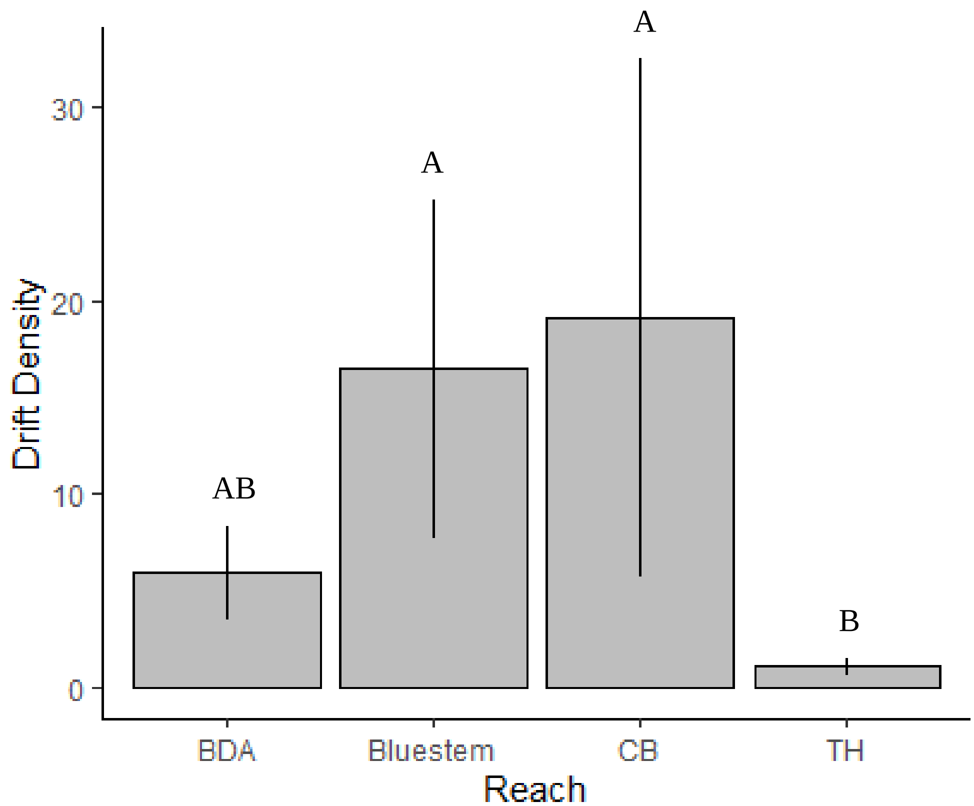

Figure 27. Mean (± se) of drifting macroinvertebrate density (# of macroinvertebrates*m^{-3}) present between the 4 reaches. Significant impacts ($p<0.05$) are denoted with A, AB, and B. A is statistically different from B.

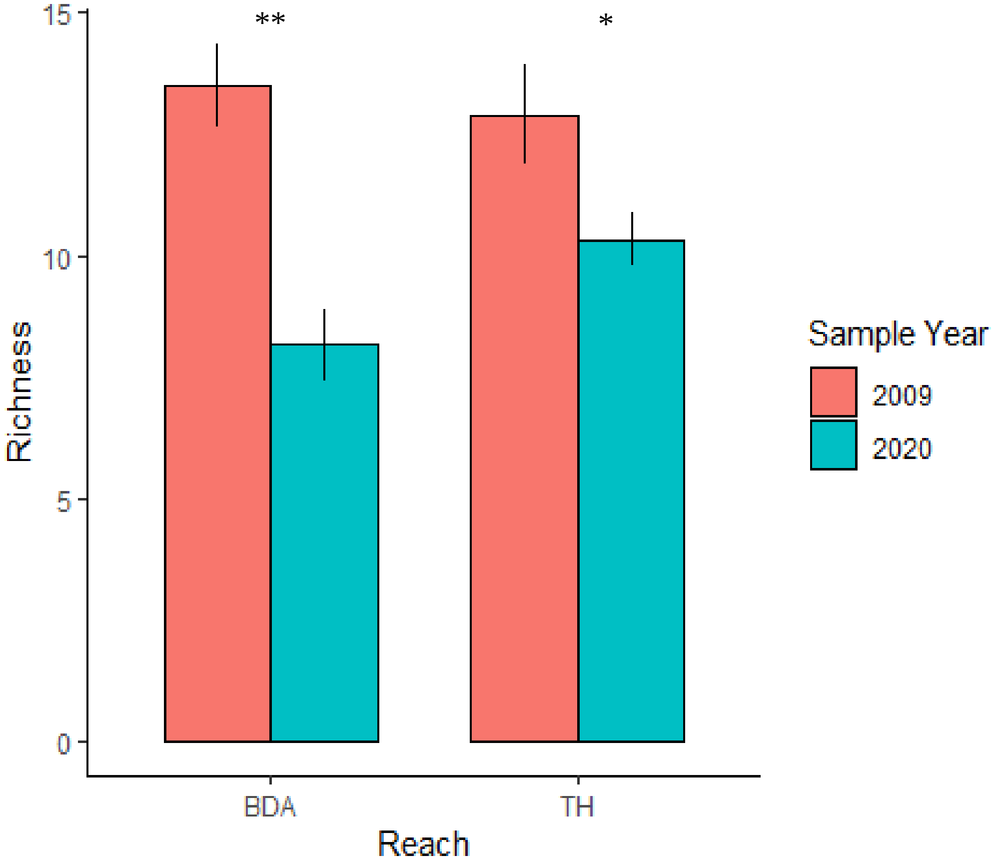

Figure 28. Mean (± se) of macroinvertebrate family richness between 2009 and 2020. Significant impacts (p<0.05) are denoted with *, and significant impacts (p<0.0001) are denoted with **.

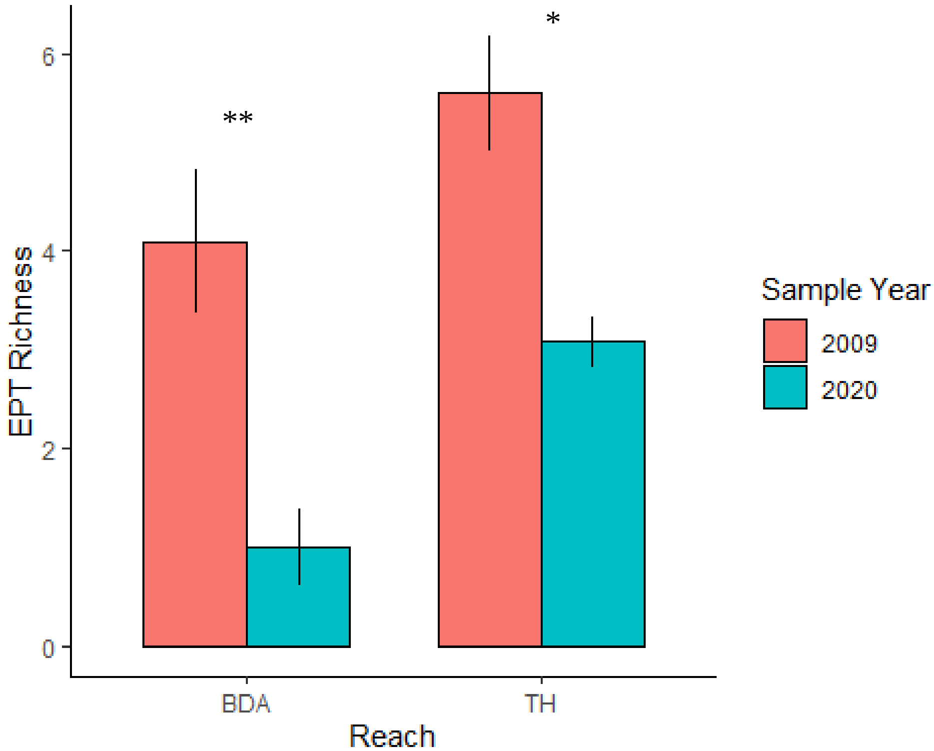

Figure 29. Mean (± se) of macroinvertebrate family Ephemeroptera, Plecoptera, Trichoptera richness between 2009 and 2020. Significant impacts (p<0.05) are denoted with *, and significant impacts (p<0.0001) are denoted with **.

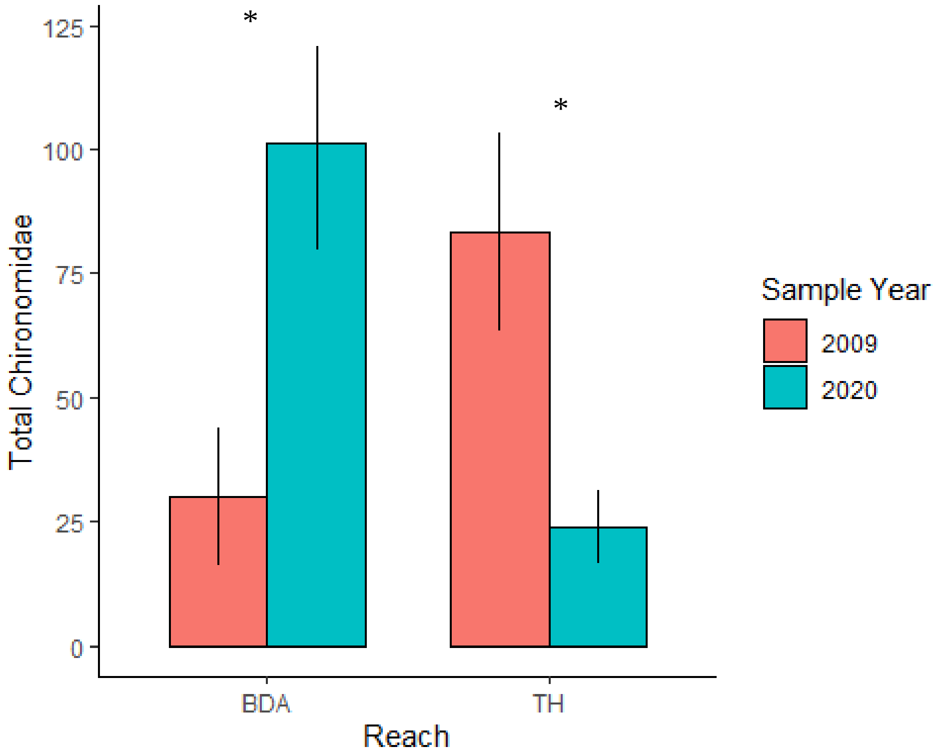

Figure 30. Mean (± se) of total Chironomidae between 2009 and 2020. Significant impacts ($p<0.05$) are denoted with *.

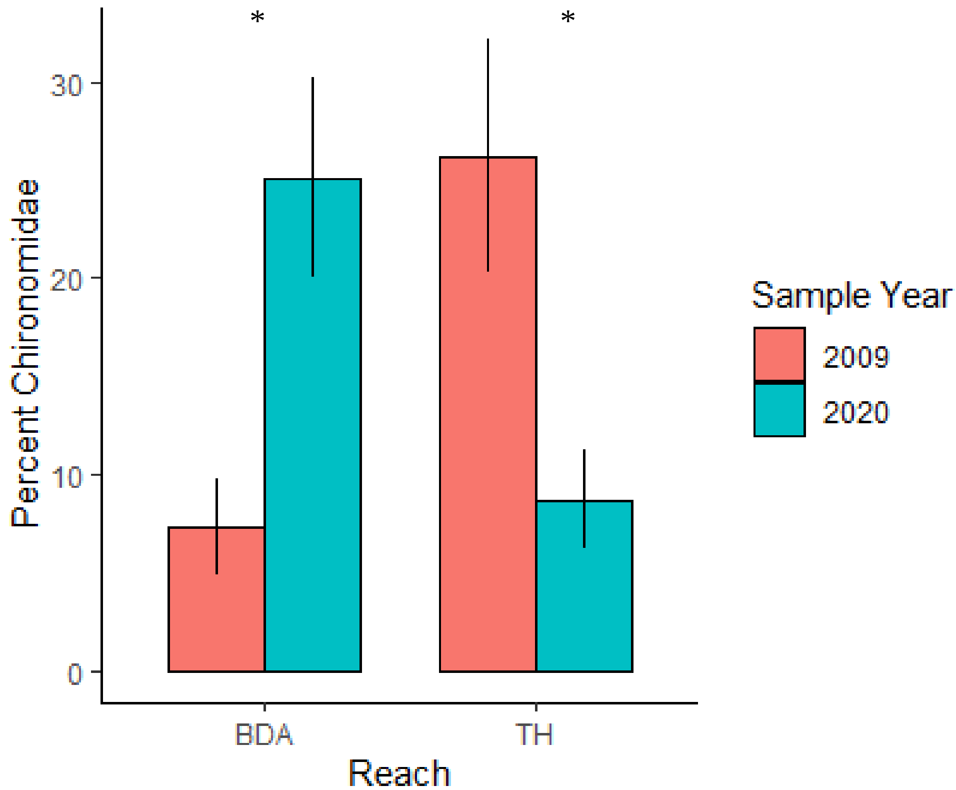

Figure 31. Mean (± se) of percent Chironomidae between 2009 and 2020. Significant impacts (p<0.05) are denoted with *.

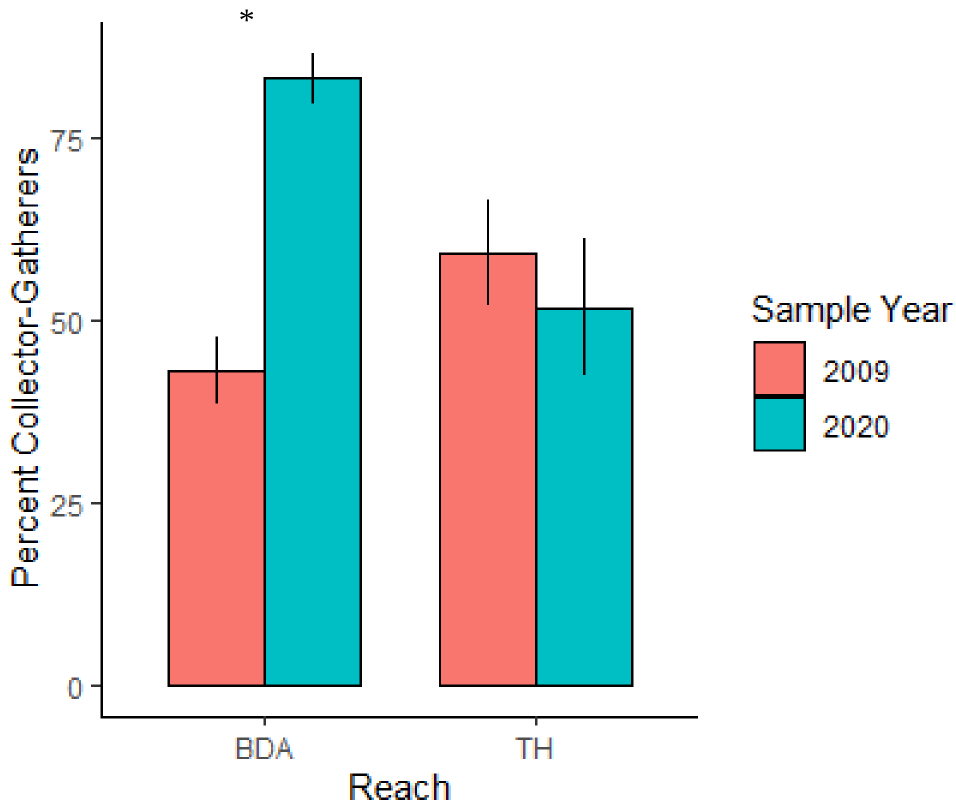

Figure 32. Mean (± se) of functional feeding group percent collector-gatherers between 2009 and 2020. Significant impacts (p<0.05) are denoted with *.

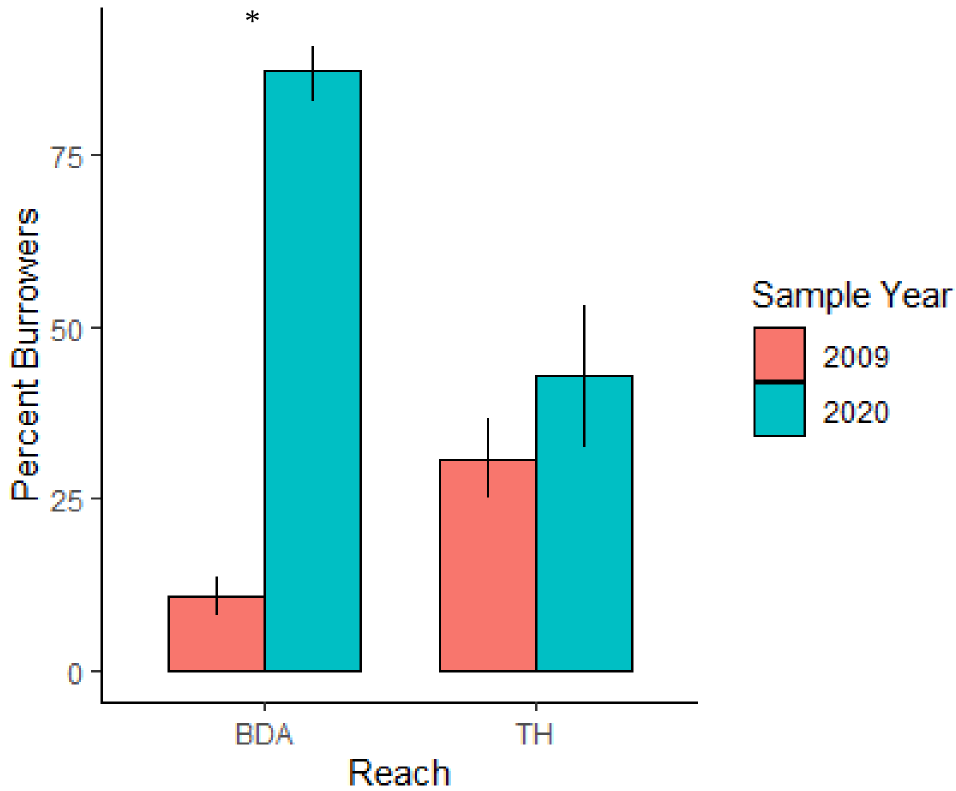

Figure 33. Mean (± se) of the functional habit group burrowers between 2009 and 2020. Significant impacts (p<0.05) are denoted with *.

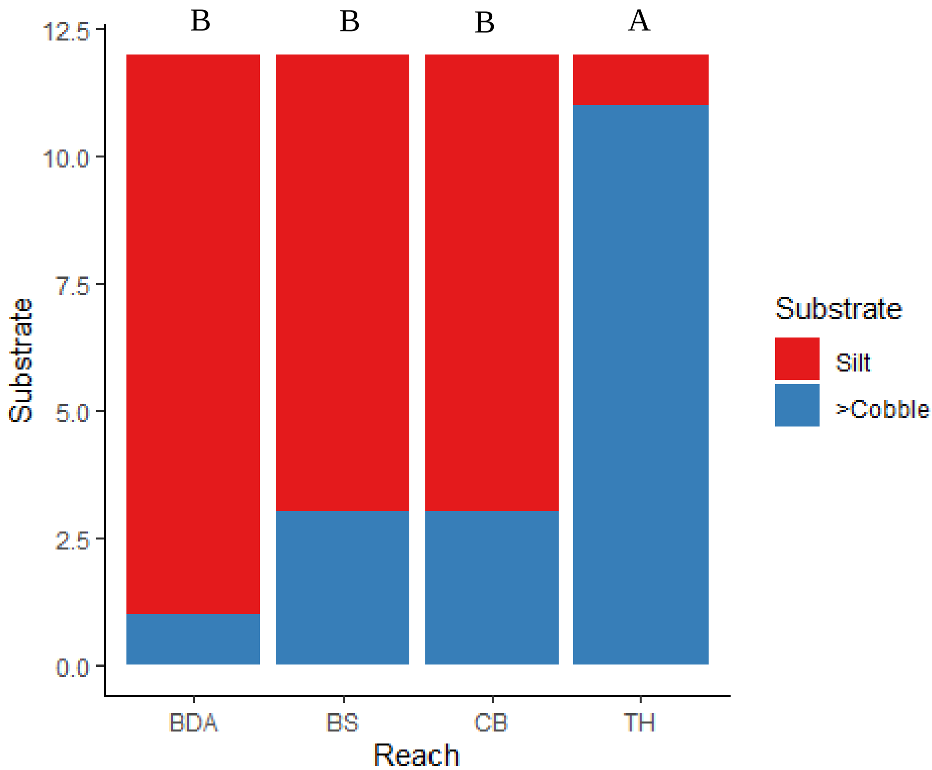

Figure 34. Count of substrate composition of each reach sampling during benthic macroinvertebrate sampling, A is statistically different from B.

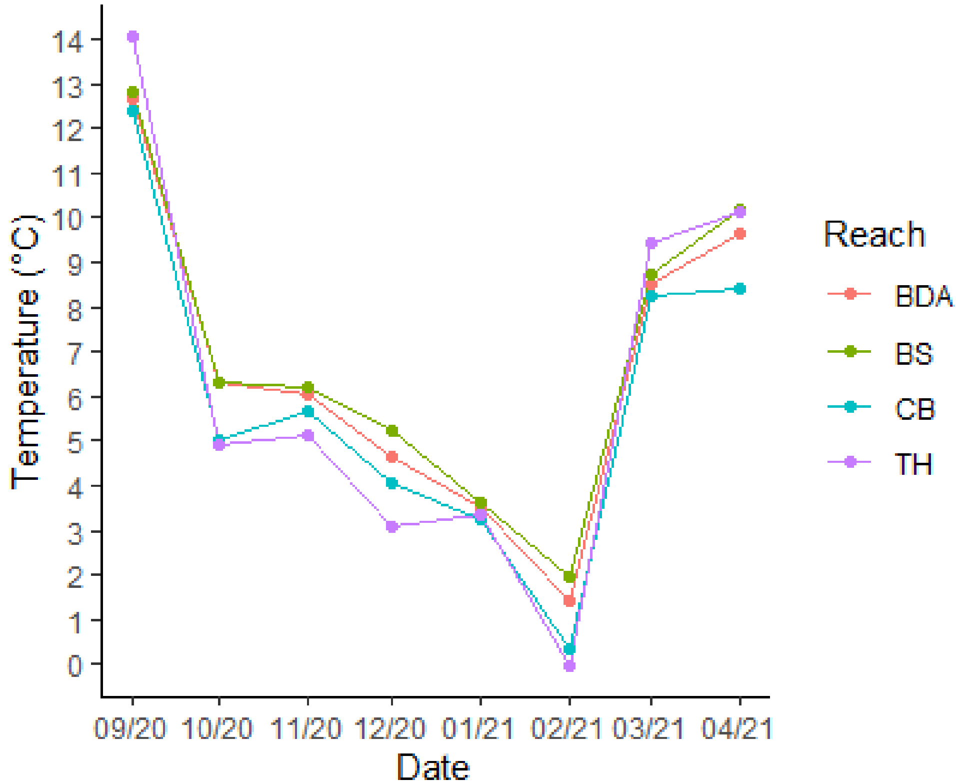

Figure 35. Temperature data for each of the 4 reaches during nutrient sampling.

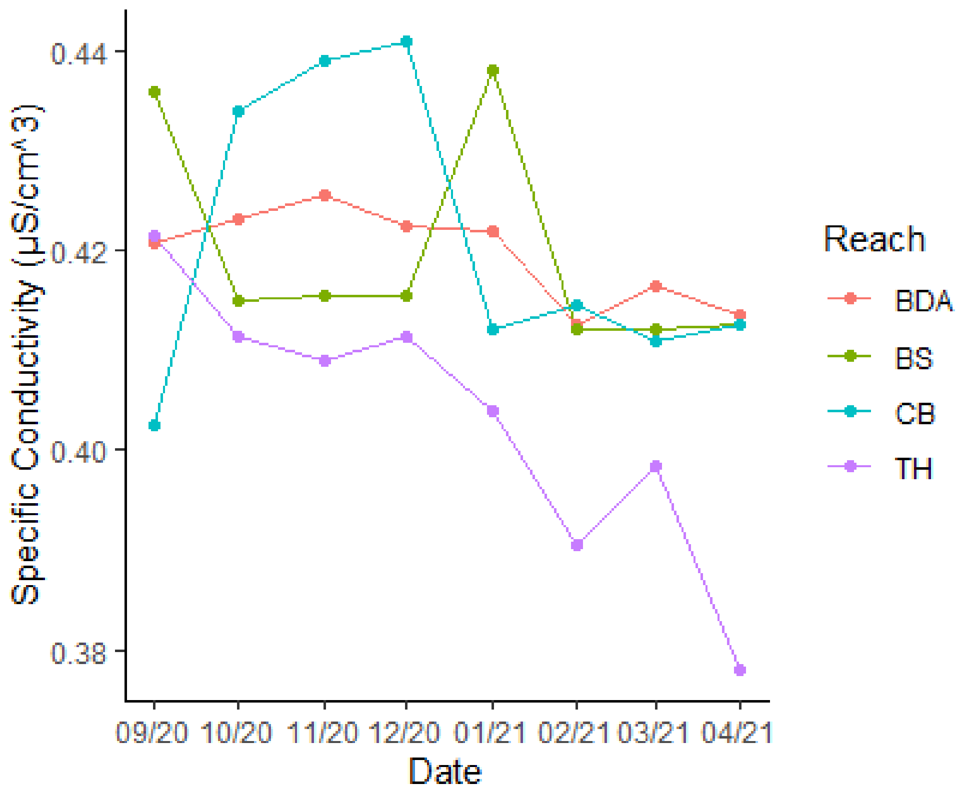

Figure 36. Specific conductivity data for each of the 4 reaches during nutrient sampling.

Table 1. Macroinvertebrate metrics for ecosystem bioassessment.

Metric	**Description**
Richness	Overall number of species sampled
EPT Richness	Number of species in the Orders Ephemeroptera, Plecoptera and Trichoptera
% Chironomid	% of individuals in the Chironomidae
% Filterers	% of individuals in the “Filterer” functional group
% Collector-Gatherers	% of individuals in the “Collector-Gatherers” functional group
Total Chironomids	Number of chironomids present
Total Abundance	Number of macroinvertebrates present per area
Biomass	Mass of macroinvertebrates per area
% Burrowers	% of individuals in the “Burrowers” functional group
Crayfish	Number of crayfish present
Total Sphaeriidae	Number of freshwater finger nail clams present
Amphipods	Number of amphipods present

Table 2. Mean and standard error values of fish abundance catch per unit effort (CPUE) present per reach.

Reach	RSS Abundance CPUE	RBT Abundance CPUE	Total Abundance CPUE
BDA	0.0775 (±0.0189)	0.0208 (±0.0056)	0.1388 (±0.0027)
BS	0.0101 (±0.0025)	0.0998 (±0.0352)	0.1437 (±0.0309)
CB	0.0068 (±0.0044)	0.0535 (±0.0227)	0.0835 (±0.1290)
TH	0.0040 (±0.0022)	0.0092 (±0.0020)	0.0511 (±0.0116)

Table 3. Results from 1-way ANOVA for fish community compositions. Significant results (p<0.05) are denoted with *.

Dependent variable	Source of variation	df	SS	MS	F	p
Total Abundance CPUE	Reach	3	2.2452	0.7484	6.849*	0.0167*
	Residuals	8	0.8742	0.1093		
Shannon's H	Reach	3	0.242	0.08066	0.413	0.748
	Residuals	8	1.562	0.19528		
RBT Abundance CPUE	Reach	3	8.546	2.8488	7.078*	0.0122*
	Residuals	8	3.22	0.4025		
BLS Abundance CPUE	Reach	3	0.0001621	5.405×10^{-5}	3.322	0.0775
	Residuals	8	0.0001302	1.627×10^{-5}		
RSS Abundance CPUE	Reach	3	0.010275	0.003425	13.38*	0.00175*
	Residuals	8	0.002047	0.000256		
SPD Abundance CPUE	Reach	3	0.0004784	0.0001595	0.431	0.736
	Residuals	8	0.0029592	0.0003699		

Table 4. Results of post-hoc Tukey HSD from 1-way ANOVA for fish community compositions. Significant results (p<0.05) are denoted with *.

Dependent variable	Reach interaction	diff	lwr	upr	p adj
Total Abundance	BS-BDA	-0.0222	-0.8866	0.8421	0.9998
	CB-BDA	-0.5320	-1.3963	0.3324	0.2741
	TH-BDA	-1.0544	-1.9188	-0.1901	0.0189
	CB-BS	-0.5098	-1.3741	0.3546	0.3043
	TH-BS	-1.0322	-1.8966	-0.1679	0.0211*
	TH-CB	-0.5225	-1.3868	0.3419	0.2867
Shannon's H	BS-BDA	-0.0524	-1.2078	1.1031	0.9988
	CB-BDA	-0.2587	-1.4141	0.8968	0.8877
	TH-BDA	0.1365	-1.0190	1.2919	0.9803
	CB-BS	-0.2063	-1.3617	0.9491	0.9378
	TH-BS	0.1888	-0.9666	1.3443	0.9510
	TH-CB	0.3951	-0.7603	1.5506	0.7021
RBT Abundance CPUE	BS-BDA	1.4407	-0.2181	3.0996	0.0906
	CB-BDA	0.8578	-0.8011	2.5166	0.4033
	TH-BDA	-0.7823	-2.4411	0.8766	0.4748
	CB-BS	-0.5830	-2.2418	1.0759	0.6853
	TH-BS	-2.2230	-3.8819	-0.5642	0.0113*
	TH-CB	-1.6400	-3.2989	0.0188	0.0526
BLS Abundance CPUE	BS-BDA	-0.0007	-0.0112	0.0099	0.9968
	CB-BDA	0.0005	-0.0101	0.0110	0.9989
	TH-BDA	0.0084	-0.0022	0.0189	0.1268
	CB-BS	0.0011	-0.0094	0.0117	0.9851
	TH-BS	0.0090	-0.0015	0.0196	0.0955
	TH-CB	0.0079	-0.0026	0.0185	0.1543
RSS Abundance CPUE	BS-BDA	-0.0643	-0.1061	-0.0225	0.0051*
	CB-BDA	-0.0675	-0.1094	-0.0257	0.0038*
	TH-BDA	-0.0703	-0.1122	-0.0285	0.0029*
	CB-BS	-0.0033	-0.0451	0.0386	0.9941
	TH-BS	-0.0061	-0.0479	0.0358	0.9650
	TH-CB	-0.0028	-0.0446	0.0390	0.9962
SPD Abundance CPUE	BS-BDA	-0.0087	-0.0590	0.0416	0.9424
	CB-BDA	-0.0178	-0.0681	0.0325	0.6815
	TH-BDA	-0.0102	-0.0605	0.0401	0.9132
	CB-BS	-0.0091	-0.0593	0.0412	0.9364
	TH-BS	-0.0015	-0.0517	0.0488	0.9997
	TH-CB	0.0076	-0.0427	0.0579	0.9606

Table 5. Results from repeated measures ANOVA for nutrient retention.

Dependent variable	Source of variation	numdf	denDF	F	p
Ammonium	Intercept	1	175	46.12601	<0.0001
	Reach	3	175	4.59144	0.004
	Location2	1	175	4.37229	0.038
	Reach:Location2	3	175	1.67905	0.1733
Nitrate	Intercept	1	175	414.0303	<0.0001
	Location2	3	175	19.2141	<0.0001
	Reach	1	175	2.1804	0.1416
	Location2:Reach	3	175	0.8355	0.476
Phosphate	Intercept	1	175	16.29469	0.0001
	Location2	3	175	4.246785	0.0063
	Reach	1	175	0.043016	0.8359
	Location2:Reach	3	175	0.341581	0.7953
Total N	Intercept	1	173	932.1346	<0.0001
	Location2	3	173	3.7406	0.0123
	Reach	1	173	1.7135	0.1923
	Location2:Reach	3	173	0.106	0.9565
Total P	Intercept	1	130	38.31333	<0.0001
	Location2	3	130	0.32242	0.8091
	Reach	1	130	0.66533	0.4162
	Location2:Reach	3	130	0.51059	0.6757

Table 6. Within-site comparisons using estimated marginal means test of ammonium, nitrate, phosphate, Total N, and Total P. Significant results (p<0.05) are denoted with *.

Dependent Variable	Reach	Contrast	Estimate	SE	DF	t ratio	p
Ammonium	BDA	Downstream-Upstream	0.005801	0.00478	175	1.213	0.2269
	BS	Downstream-Upstream	0.01346	0.00478	175	2.814	0.0054*
	CB	Downstream-Upstream	0.000583	0.00473	175	0.123	0.902
	TH	Downstream-Upstream	0.00025	0.00473	175	0.053	0.9579
Nitrate	BDA	Downstream-Upstream	-0.0147	0.0639	175	-0.23	0.8183
	BS	Downstream-Upstream	-0.13065	0.0639	175	-2.045	0.0423*
	CB	Downstream-Upstream	-0.04241	0.0632	175	-0.671	0.5029
	TH	Downstream-Upstream	-0.00097	0.0632	175	-0.015	0.9878
Phosphate	BDA	Downstream-Upstream	0.001035	0.0022	175	0.47	0.6392
	BS	Downstream-Upstream	0.001321	0.0022	175	0.599	0.5497
	CB	Downstream-Upstream	0.000113	0.00218	175	0.052	0.9587
	TH	Downstream-Upstream	-0.00152	0.00218	175	-0.697	0.487
Total N	BDA	Downstream-Upstream	0.0452	0.0757	173	0.598	0.5509
	BS	Downstream-Upstream	0.027	0.0765	173	0.353	0.7246
	CB	Downstream-Upstream	0.085	0.07575	173	1.123	0.2629
	TH	Downstream-Upstream	0.0422	0.0786	173	0.537	0.592
Total P	BDA	Downstream-Upstream	-0.00382	0.00492	130	-0.776	0.4389
	BS	Downstream-Upstream	-0.00271	0.005	130	-0.543	0.5883
	CB	Downstream-Upstream	0.00312	0.00492	130	0.634	0.5275
	TH	Downstream-Upstream	-0.00466	0.00492	130	-0.948	0.345

Table 7. Mean and standard error values of benthic macroinvertebrate metrics per reach.

Reach	Richness	Abundance	EPT Richness	Total Chironomidae	Percent Chironomidae	Biomass	Amphipods	Sphaeriidae	Percent Collector-Gatherers	Percent Burrowers
BDA	8.167 (±0.737)	81582.44 (±15790.78)	0.9167 (±0.3362)	1649.33 (±348.81)	26.30 (±5.12)	48719.81 (±17241.07)	595.25 (±320.11)	112.33 (±63.03)	87.38 (±2.73)	87.10 (±4.56)
BS	9.417 (±0.543)	56904.12 (±6820.14)	1.4167 (±0.2600)	631.58 (±136.28)	15.05 (±3.73)	5371.97 (±1230.34)	519.00 (±281.67)	127.17 (±60.48)	75.95 (±5.51)	69.48 (±6.91)
CB	10.834 (±0.767)	78074.37 (±9259.09)	1.7500 (±0.3286)	785.33 (±154.14)	13.70 (±3.60)	19757.24 (±6939.21)	1544.50 (±388.27)	179.08 (±139.69)	57.54 (±7.25)	52.95 (±9.17)
TH	10.167 (±0.474)	29269.71 (±7607.18)	3.0833 (±0.2600)	205.58 (±72.66)	8.71 (±2.55)	4898.82 (±1591.62)	16.58 (±9.55)	4.42 (±2.46)	51.92 (±9.50)	43.47 (±10.56)

Table 8. Results from 1-way ANOVA for benthic macroinvertebrate metrics. Significant results (p<0.05) are denoted with *.

Dependent variable	Source of variation	df	SS	MS	F	p
Richness	Reach	3	47.06	15.687	3.167	0.0336*
	Residuals	44	217.92	4.953		
Total Abundance	Reach	3	2.09E+10	6.95E+09	5.273	0.0034*
	Residuals	44	5.80E+10	1.32E+09		
Total Chironomidae	Reach	3	55.4	18.514	12.86	3.63E-06*
	Residuals	44	63.33	1.439		
Percent Chironomidae	Reach	3	0.2172	0.0724	3.71	0.0183*
	Residuals	44	0.8586	0.01951		
Crayfish	Reach	3	0.645	0.215	0.963	0.418
	Residuals	44	9.82	0.2232		
Amphipods	Reach	3	181.1	60.38	22.19	6.64E-09*
	Residuals	44	119.7	2.72		
Sphaeriidae	Reach	3	57.91	19.302	5.13	0.00395*
	Residuals	44	165.55	3.762		
Percent Filterers	Reach	3	0.1741	0.05802	2.138	0.0886
	Residuals	44	1.1016	0.02504		
Percent Collector-Gatherers	Reach	3	1.312	0.4373	5.865	0.00185*
	Residuals	44	3.281	0.0746		
Percent Burrowers	Reach	3	2.045	0.6818	5.99	0.00163*
	Residuals	44	5.009	0.1138		
EPT Richness	Reach	3	4.874	1.6248	7.902	0.000252*
	Residuals	44	9.047	0.2056		
Biomass	Reach	3	27.82	9.274	4.015	0.0131*
	Residuals	44	101.63	2.31		

Table 9. Results of post-hoc Tukey HSD from 1-way ANOVA for benthic macroinvertebrate composition. Significant results (p<0.05) are denoted with *.

Dependent variable	Reach interaction	diff	lwr	upr	p adj
Richness	BS-BDA	1.2500	-1.1758	3.6758	0.5208929
	CB-BDA	2.6667	0.2409	5.092469	0.0261665*
	TH-BDA	2.0000	-0.4258	4.425803	0.1387742
	CB-BS	1.4167	-1.0091	3.842469	0.4119584
	TH-BS	0.7500	-1.6758	3.175803	0.8420829
	TH-CB	-0.6667	-3.0925	1.759136	0.8829758
Total Abundance	BS-BDA	-24678.3150	-64256.7300	14900.0950	0.3541705
	CB-BDA	-3508.0650	-43086.4800	36070.346	0.9952658
	TH-BDA	-52312.7240	-91891.1300	-12734.313	0.0052821*
	CB-BS	21170.2510	-18408.1600	60748.662	0.4889749
	TH-BS	-27634.4090	-67212.8200	11944.002	0.2581048
	TH-CB	-48804.6600	-88383.0700	-9226.249	0.0102179*
Total Chironomidae	BS-BDA	-0.9721	-2.2799	0.3356	0.2092006
	CB-BDA	-0.6918	-1.9995	0.6159228	0.4984979
	TH-BDA	-2.9007	-4.2084	-1.5929396	0.0000026*
	CB-BS	0.2803	-1.0274	1.5880669	0.9397942
	TH-BS	-1.9285	-3.2362	-0.6207955	0.0015965*
	TH-CB	-2.2089	-3.5166	-0.9011367	0.0002709*
Percent Chironomidae	BS-BDA	-0.1187	-0.2709	0.0336	0.1752533
	CB-BDA	-0.1325	-0.2847	0.01979348	0.1082664
	TH-BDA	-0.1837	-0.3359	-0.03138755	0.0124216*
	CB-BS	-0.0138	-0.1661	0.13846972	0.9949441
	TH-BS	-0.0650	-0.2173	0.08728869	0.6674491
	TH-CB	-0.0512	-0.2035	0.10108898	0.8061847
Crayfish	BS-BDA	-0.1155	-0.6305	0.3994	0.9318248
	CB-BDA	-0.3226	-0.8376	0.1923502	0.3500524
	TH-BDA	-0.1253	-0.6403	0.3896105	0.9150297
	CB-BS	-0.2071	-0.7220	0.3078747	0.7071777
	TH-BS	-0.0098	-0.5248	0.505135	0.9999519
	TH-CB	0.1973	-0.3177	0.7122106	0.7370797
Amphipods	BS-BDA	0.5715	-1.2264	2.3695	0.8308256
	CB-BDA	2.3372	0.5392	4.135144	0.0062298*
	TH-BDA	-3.0514	-4.8493	-1.253404	0.000253*
	CB-BS	1.7656	-0.0323	3.563603	0.0559318
	TH-BS	-3.6229	-5.4209	-1.824945	0.0000158*
	TH-CB	-5.3885	-7.1865	-3.590593	0.000E+00*
Sphaeriidae	BS-BDA	-1.3563	2.8724	0.7741416	0.7741416
	CB-BDA	0.7567	-1.3576	2.8710556	0.7750479

	TH-BDA	-1.9290	-4.0434	0.185318	0.0850306
	CB-BS	-0.0013	-2.1156	2.1130357	1.0000
	TH-BS	-2.6870	-4.8014	-0.5727019	0.0077401*
	TH-CB	-2.6857	-4.8001	-0.5713982	0.0077756*
Percent Filterers	BS-BDA	0.0400	-0.1325	0.2124201	0.9256374
	CB-BDA	0.1299	-0.0426	0.3023252	0.1997823
	TH-BDA	0.1435	-0.0290	0.3159274	0.1334611
	CB-BS	0.0899	-0.0826	0.2623749	0.5110908
	TH-BS	0.1035	-0.0690	0.2759772	0.3878343
	TH-CB	0.0136	-0.1589	0.1860721	0.9966493
Percent Collector-Gatherers	BS-BDA	-0.1443	-0.4420	0.1533	0.571169
	CB-BDA	-0.3630	-0.6607	-0.06538178	0.0112668*
	TH-BDA	-0.4072	-0.7048	-0.10953194	0.0037056*
	CB-BS	-0.2187	-0.5164	0.07894646	0.2179842
	TH-BS	-0.2629	-0.5605	0.0347963	0.1005859
	TH-CB	-0.0442	-0.3418	0.25350176	0.978682
Percent Burrowers	BS-BDA	-0.2452	-0.6130	0.1226	0.2963441
	CB-BDA	-0.4509	-0.8186	-0.08311621	0.0107602*
	TH-BDA	-0.5343	-0.9021	-0.16657353	0.0019005*
	CB-BS	-0.2057	-0.5734	0.16208764	0.450141
	TH-BS	-0.2891	-0.6569	0.07863033	0.1693186
	TH-CB	-0.0835	-0.4512	0.28430634	0.9296617
EPT Richness	BS-BDA	0.3084	-0.1858	0.8027	0.3534788
	CB-BDA	0.4142	-0.0801	0.9084314	0.1291518
	TH-BDA	0.8875	0.3932	1.3817703	0.0001088*
	CB-BS	0.1057	-0.3886	0.5999896	0.9401853
	TH-BS	0.5790	0.0848	1.0733284	0.0158955*
	TH-CB	0.4733	-0.0209	0.9676192	0.0649569
Biomass	BS-BDA	-1.6532	-3.3099	0.0034	0.0506499*
	CB-BDA	-0.6056	-2.2623	1.051046658	0.7636965
	TH-BDA	-1.8601	-3.5168	-0.203455918	0.0222989*
	CB-BS	1.0476	-0.6090	2.704289687	0.341842
	TH-BS	-0.2069	-1.8635	1.44978711	0.98705
	TH-CB	-1.2545	-2.9112	0.402147733	0.1956005

Table 10. Macroinvertebrate drift Kruskall-Wallis test. Significant results ($p<0.05$) are denoted with *.

Dependent Variable	Chi-Squared	df	p value
Baetidae nymph	8.0298	3	0.0454*
Oligochaetes	8.9749	3	0.02963*
Ephemeroptera adults	3.9391	3	0.2681
Tricorythodes nymphs	12.104	3	0.007036*
Gammarus	15.067	3	0.00176*
Nematocera	2.2559	3	0.521
Drift Density	9.6067	3	0.02222*

Table 11. Drift macroinvertebrate Dunns test with Benjamini Hochberg method. Significant results (p<0.05) are denoted with *.

Dependent Variable	Comparison	Z	p unadj	p adj
Baetidae nymph	BDA-BS	-1.2301	0.218658	0.32798678
	BDA-CB	-1.1481	0.250928	0.30111381
	BS-CB	0.082007	0.934641	0.93464116
	BDA-TH	1.230105	0.218658	0.4373157
	BS-TH	2.46021	0.013886	0.08331352
	CB-TH	2.378203	0.017397	0.05219178
Oligochaetes	BDA-BS	-0.41139	0.680786	0.81694352
	BDA-CB	0.02057	0.983589	0.98358905
	BS-CB	0.43196	0.665771	0.99865578
	BDA-TH	2.283217	0.022418	0.06725278
	BS-TH	2.694607	0.007047	0.04228297*
	CB-TH	2.262647	0.023657	0.04731487*
Ephemeroptera adults	BDA-BS	0.689828	0.490303	0.5883632
	BDA-CB	-0.11497	0.908468	0.9084679
	BS-CB	-0.8048	0.420936	0.6314037
	BDA-TH	-1.26468	0.205985	0.617954
	BS-TH	-1.95451	0.050641	0.3038446
	CB-TH	-1.14971	0.250262	0.5005245
Tricorythodes nymphs	BDA-BS	-2.57867	0.009918	0.02975478*
	BDA-CB	-2.10037	0.035697	0.05354511
	BS-CB	0.478301	0.632436	0.75892321
	BDA-TH	0.187161	0.851534	0.85153421
	BS-TH	2.765827	0.005678	0.03406716*
	CB-TH	2.287526	0.022165	0.04433024*
Gammarus	BDA-BS	1.487919	0.136772	0.205158279
	BDA-CB	-0.70263	0.482287	0.48228727
	BS-CB	-2.19055	0.028485	0.056969063
	BDA-TH	2.851845	0.004347	0.013039876
	BS-TH	1.363926	0.172591	0.20710903
	CB-TH	3.554474	0.000379	0.002272417*
Nematocera	BDA-BS	-1.48825	0.136685	0.8201084
	BDA-CB	-0.74413	0.456801	0.6852009
	BS-CB	0.744126	0.456801	0.9136012
	BDA-TH	-0.57876	0.562748	0.6752979
	BS-TH	0.909487	0.363093	1
	CB-TH	0.165361	0.86866	0.8686597
Drift Density	BDA-BS	-0.77567	0.437943	0.65691423
	BDA-CB	-0.3266	0.743971	0.74397148
	BS-CB	0.449073	0.653379	0.78405469
	BDA-TH	2.082066	0.037336	0.07467283
	BS-TH	2.857738	0.004267	0.02560035*
	CB-TH	2.408665	0.016011	0.04803297*

Table 12. Mean and standard error values of Klinzing comparison per reach and year.

Reach	Sample Year	Richness	EPT Richness	Total Chironomidae	Percent Chironomidae	Percent Collector-Gatherers	Percent Burrowers
BDA	2009	13.5 (±0.9)*	4.10 (±0.72)*	30.2 (±13.9)*	0.0730 (±0.0242)*	0.432 (±0.045)*	0.108 (±0.027)*
BDA	2020	8.2 (±0.8)*	1.00 (±0.39)*	101.2 (±21.7)*	0.251 (±0.051)*	0.833 (±0.035)*	0.874 (±0.045)*
TH	2009	12.9 (± 1.0)*	5.60 (±0.58)*	83.5(±19.9)*	0.262 (± 0.060)*	0.593 (±0.072)	0.309 (±0.059)
TH	2020	10.3 (±0.5)*	3.08 (±0.26)*	23.9(±7.4)*	0.0870 (±0.254)*	0.519 (±0.095)	0.429 (±0.103)

Table 13. Results from 2-way ANOVA (Site and Sample Year) for the Klinzing comparison. Significant results (p<0.05) are denoted with *.

Dependent variable	Source of variation	df	SS	MS	F	p
Richness	Reach	1	9.09	9.09	1.348	0.2525*
	Sample Year	1	170.21	170.21	25.241	1.10E-05*
	Reach*Sample Year	1	20.88	20.88	3.096	0.0861
	Residuals	40	269.73	6.74		
EPT Richness	Reach	1	4	4.122	23.424	1.97E-05*
	Sample Year	1	6.097	6.097	34.651	6.82E-07*
	Reach*Sample Year	1	0.87	0.87	4.946	0.0319*
	Residuals	40	7.038	0.176		
Total Chironomidae	Reach	1	0.47	0.474	0.302	0.585553
	Sample Year	1	1.19	1.193	0.76	0.388597
	Reach*Sample Year	1	25.23	25.231	16.075	0.000259*
	Residuals	40	62.78	1.57		
Amphipods	Reach	1	15.54	15.398	11.194	0.00179*
	Sample Year	1	0.18	0.1181	0.131	0.71888
	Reach*Sample Year	1	1.69	1.691	1.229	0.27421
	Residuals	40	55.02	1.376		
Crayfish	Reach	1	0.051	0.0514	0.339	0.56375
	Sample Year	1	1.827	1.8271	12.042	0.00126*
	Reach*Sample Year	1	0.043	0.0428	0.282	0.59808
	Residuals	40	6.069	0.1517		
Sphaeriidae	Reach	1	5.88	5.875	5.126	0.02906*
	Sample Year	1	8.96	8.963	7.82	0.0079*
	Reach*Sample Year	1	12.24	12.243	10.682	0.00223
	Residuals	40	45.85	1.146		
Percent Chironomidae	Reach	1	0.0001	0.0001	0.004	0.947283
	Sample Year	1	0	0	0	0.990783
	Reach*Sample Year	1	0.3715	0.3715	16.4	0.000229*
	Residuals	40	0.906	0.0226		
Percent Filterers	Reach	1	0.0317	0.03167	0.933	0.34
	Sample Year	1	0.013	0.01305	0.385	0.539
	Reach*Sample Year	1	0.02	0.02004	0.591	0.447
	Residuals	40	1.3572	0.03393		
	Reach	1	0.192	0.1923	2.026	0.16239

Percent Collector-Gatherers	Sample Year	1	0.793	0.7929	8.353	0.00619*
	Reach*Sample Year	1	1.028	1.0281	10.831	0.00209*
	Residuals	40	3.797	0.0949		
Percent Burrowers	Reach	1	0.698	0.698	7.152	0.0108*
	Sample Year	1	4.073	4.073	41.722	1.07E-07*
	Reach*Sample Year	1	1.976	1.976	20.24	5.75E-05*
	Residuals	40	3.905	0.098		

Table 14. Within-site comparisons using estimated marginal means test of the Klinzingcomparison. Significant results (p<0.05) are denoted with *.

Dependent variable	Reach	Year	Estimate	SE	df	T ratio	P value
Richness	BDA	2009-2020	5.33	1.11	40	4.797	<0.0001*
	TH	2009-2020	2.57	1.11	40	2.308	0.0262*
EPT Richness	BDA	2009-2020	1.03	0.18	40	5.735	<0.0001*
	TH	2009-2020	0.465	0.18	40	2.59	0.0133*
Total Chironomidae	BDA	2009-2020	-1.85	0.536	40	-3.451	0.0013*
	TH	2009-2020	1.19	0.536	40	2.219	0.0322*
Amphipods	BDA	2009-2020	-0.265	0.502	40	-0.528	0.6007
	TH	2009-2020	0.522	0.502	40	1.04	0.3045
Crayfish	BDA	2009-2020	-0.472	0.167	40	-2.83	0.0073*
	TH	2009-2020	-0.347	0.167	40	-2.078	0.0442*
Sphaeriidae	BDA	2009-2020	-1.966	0.458	40	-4.288	0.0001*
	TH	2009-2020	0.153	0.458	40	0.334	0.7403
Percent Chironomidae	BDA	2009-2020	-0.185	0.0644	40	-2.872	0.0065*
	TH	2009-2020	0.184	0.0644	40	2.855	0.0068*
Percent Filterers	BDA	2009-2020	-0.00828	0.0789	40	-0.105	0.9169
	TH	2009-2020	0.07745	0.0789	40	0.982	0.332
Percent Collector-Gatherers	BDA	2009-2020	-0.5766	0.132	40	-4.371	0.0001*
	TH	2009-2020	0.0374	0.132	40	0.284	0.7782
Percent Burrowers	BDA	2009-2020	-1.037	0.134	40	-7.748	<0.0001*
	TH	2009-2020	-0.185	0.134	40	-1.386	0.1734

Table 15. Summary of substrate counts present at benthic macroinvertebrate sampling locations.

Reach	Silt	>Cobble
BDA	11	1
BS	9	3
CB	9	3
TH	1	11

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